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VOLUME III: MODEL DEVELOPMENT

CONTRACT NO. N00039-77-C-0100

Prepared for

NAVAL ELECTRONICS SYSTEM COMMAND

Prepared by

P. Titterton, H. Sweeney, W. Scott,
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GTE SYLVANIA
INCORPORATED
ELECTRONIC SYSTEMS GROUP/WESTERN DIVISION

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THIS STUDY EXPLORED THE CAPABILITY OF BLUE-GREEN OPTICAL COMMUNICATIONS TO PERFORM WIDE AREA BROADCAST TO SUBMERGED SUBMARINES. EMERGENCY ACTION MESSAGES, SELECTIVE CALL MESSAGES, AND GENERAL BROADCAST TRAFFIC WERE SPECIFICALLY ADDRESSED.

AS A RESULT OF OPERATING CONCEPT SELECTION, MODEL DEVELOPMENT AND PRELIMINARY PERFORMANCE EVALUATION, IT HAS BEEN CONCLUDED THAT THE SYSTEM IS FEASIBLE AND OPTICAL COMMUNICATIONS CAN BE MAINTAINED FROM ORBITING SATELLITES TO SUBMERGED SUBMARINES.

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(OSCAR)

VOLUME III: Model Development

Prepared for

Naval Electronic Systems Command

Contract N00039-77-C-0100

Prepared by

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Section I

INTRODUCTION AND SUMMARY

This is Volume III, OSCAR System Model Development, of the final report on Phase IA of the Optical Submarine Communications by Aerospace Relay (OSCAR) program, performed by GTE Sylvania under Contract Number N00039-77-C-0100. The model has been developed as a design tool, and is used to evaluate performance of alternate designs, and assess critical technology.

The ability to provide a communication link between aerospace relays and submarines at operating depths would significantly enhance the NAVY's command, control and communications (C^3) capability. The most promising technology for accomplishing this objective is optical communications that exploit the blue-green transmission characteristics of seawater.

The Naval Electronics System Command has defined a program for using optical communications for certain specific NAVY C^3 requirements. The program, "Optical Submarine Communications by Aerospace Relay" (OSCAR), explores the capability of optical communications to perform wide area broadcast to submerged submarines. General broadcast traffic, Emergency Action Messages, and Selective Call messages are specifically addressed by the OSCAR program.

The three major parts of the OSCAR phase IA program are:

1. Operating Concept Selection, reported in Volume II.
2. Model Development, reported in this volume;
3. System Definition, reported in Volume IV.*

Volume II, Operating Concept Definition, analyzed all the logical concepts for meeting the system requirements, and selected one concept for further study. The selected concept uses a radio frequency uplink to satellites at or near synchronous altitudes, and a blue-green laser downlink from the satellites to the operational area. This selection was based on a top level and approximate model relating all requirements (except system effectiveness) to the system concept(s).

* Volume I contains an Executive Summary of the entire program.

1. (Continued)

This volume presents the OSCAR system modeling (developed subsequent to the Operating Concept Selection) for describing all aspects of the OSCAR performance i.e., an analytic model relating system requirements, the operating environment, and system design to system performance. The earlier model has been revised and expanded to include all the practical aspects of actual system behavior, so that a more precise estimate of the system performance for a given system design is available.

The logical development of a complete OSCAR system model is shown in Figure 1-1, while Figure 1-2 shows another view of the three levels of detail involved. The first step is a detailed model for the signal and noise characteristics of the optical downlink on a pulse by pulse basis. The second step is to incorporate these pulses in a communication message, and treat the downlink communications and scanning aspects of OSCAR during a single time interval. Only one portion of the total required coverage area is treated at a time since the model applies to a single satellite during a single time interval. The full system effectiveness is not included since only the communication "downlink" availability is analyzed.

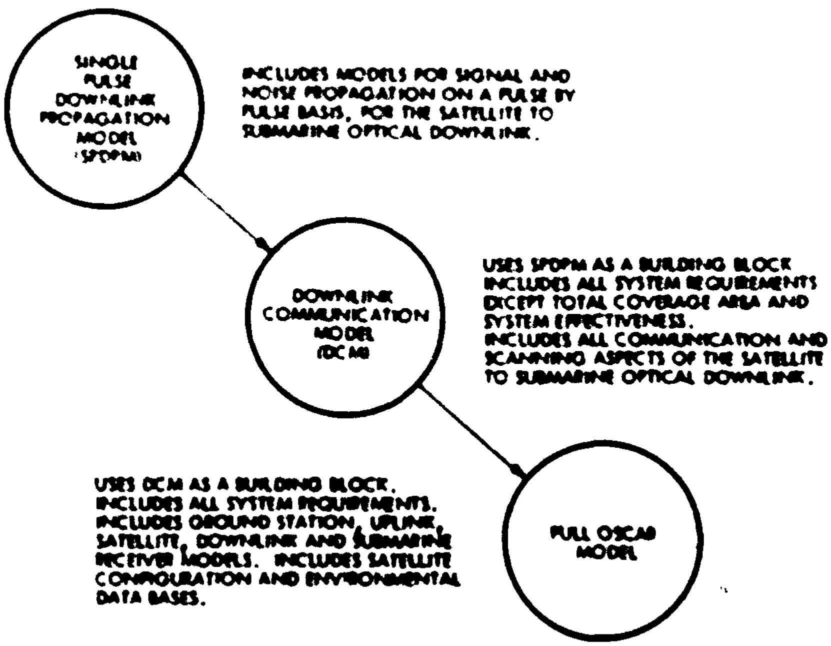

Figure 1-1. Development Procedure for a Full OSCAR Model

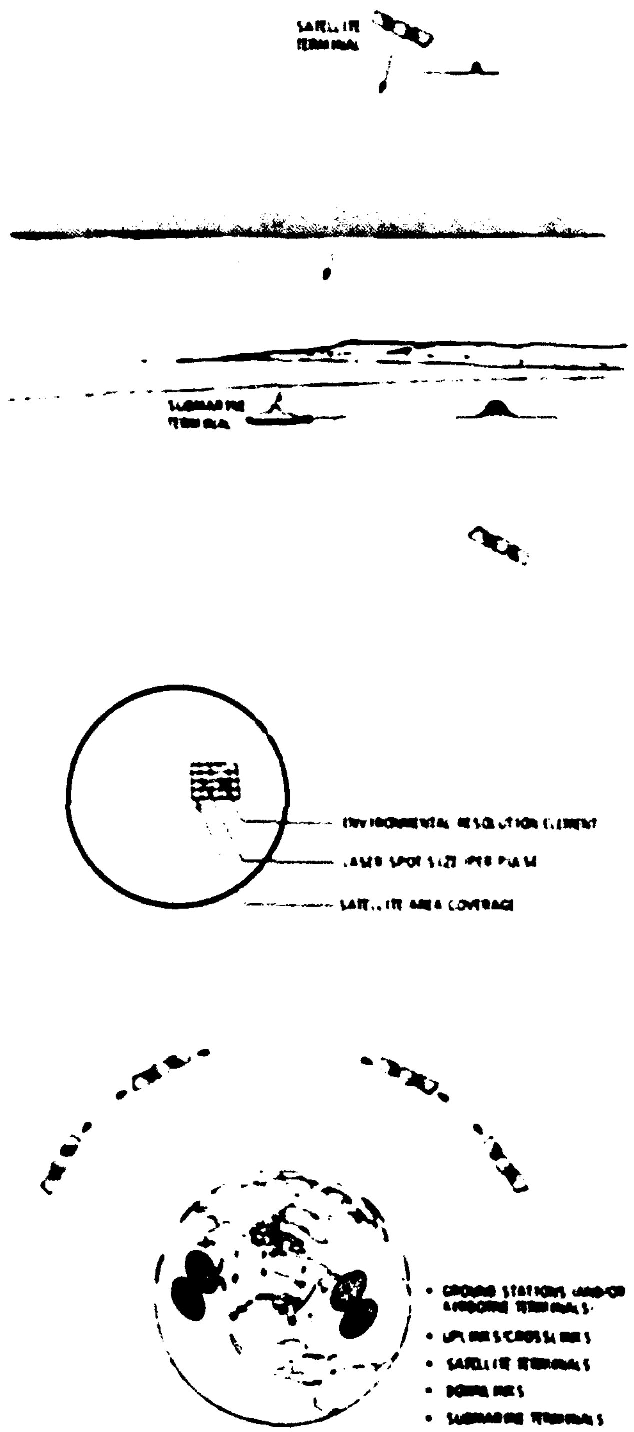

Figure 1-2. Representation of OSCAR Model Development

1. (Continued)

The third step, the Full OSCAR Model, treats all aspects of system behavior including the uplink, evolving data bases, time varying locations of background sources, and the complete satellite constellation. The full system effectiveness is included.

This report presents all three steps in the complete OSCAR model: the Single Pulse Downlink Propagation Model (SPDPM), the Downlink Communication Model (DCM), and the Full OSCAR System Model (FOSM), as well as a Glossary of all symbols used in these models. (The Glossary is described in Section 2.0.)

A draft of the SPDPM was submitted on July 1, 1978. Extensive review, by both NAVY and Government Contractor personnel over the succeeding eleven months, has led to some minor revisions. The approved version is presented in this report.

Section 3 discusses all aspects of the signal portion of the single pulse downlink propagation model. The parameters used are shown in Figure 1-3. The laser pulse originates on the satellite, propagates through the atmosphere (including whatever clouds are present), the air-water interface and the water, and is detected by the submarine receiver.

Section 4 discusses all aspects of the noise portion of the single pulse downlink propagation model. Some portions of the background light (sunlight, moonlight) traverse a path like that of the signal (although usually at a different zenith angle), while other portions of it (blue sky-light and star-light/zodiacal light) do not arise from single point-like sources, and must be treated differently. The bioluminescent light originates from sources in the water itself, and so the atmospheric conditions have no direct effects on its properties.

Sections 3 and 4 are organized in the same manner. First the method of approach used in the models is discussed, and then a detailed flow chart showing the interactions between all the equations is illustrated. (A top level schematic of these flow charts is shown in Figure 1-4). The second subsection defines and discusses all the input information needed to perform the calculations. The third subsection (3.3 and 4.3 respectively) contains the derivations and justifications of all the equations used. These equations and derivations are organized in a discrete modular fashion, so that future revision (e.g., cloud and water models) may be made in an efficient and inexpensive manner.

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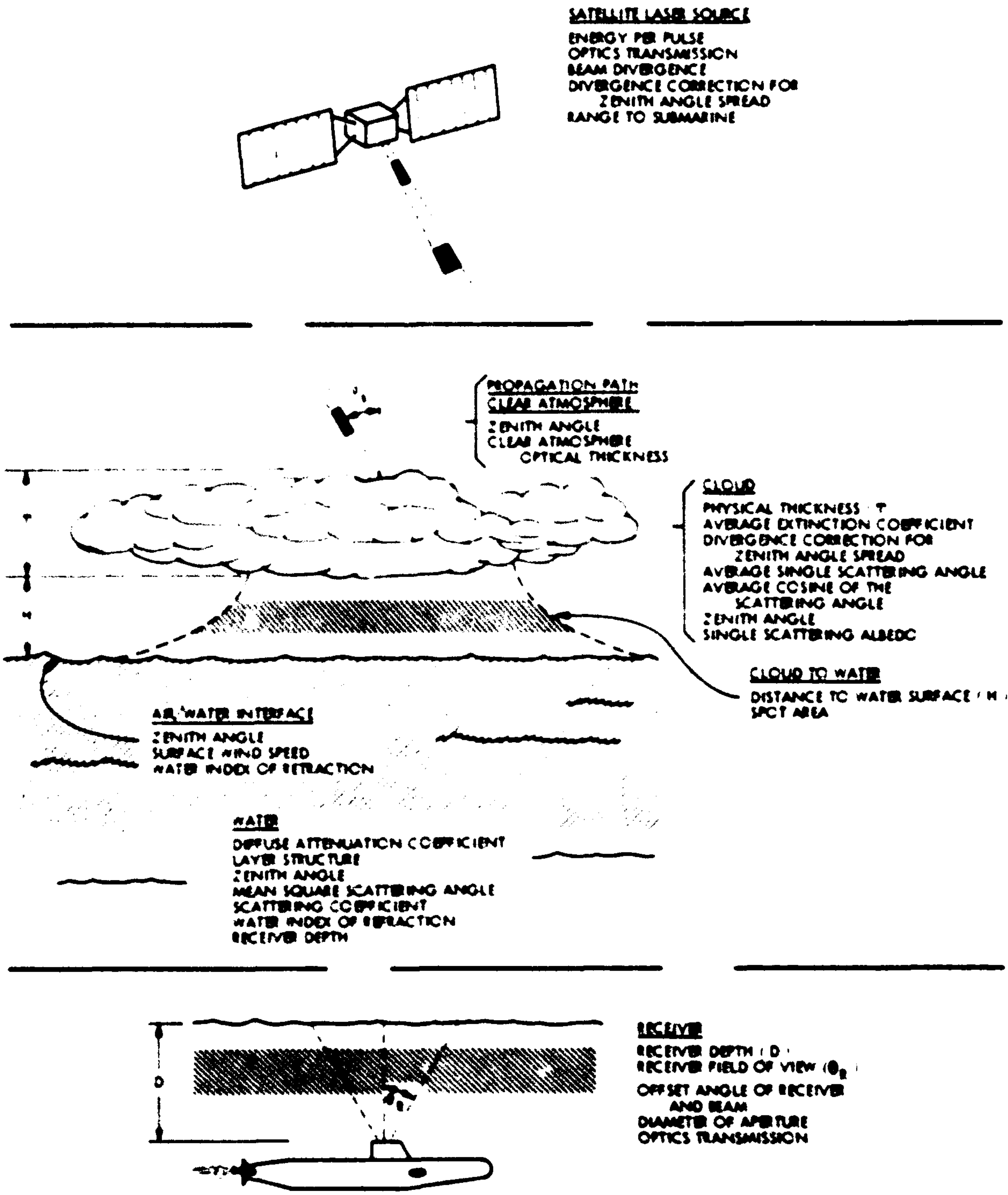

Figure 1-3. Parameters for the Single-Pulse Signal Downlink Model

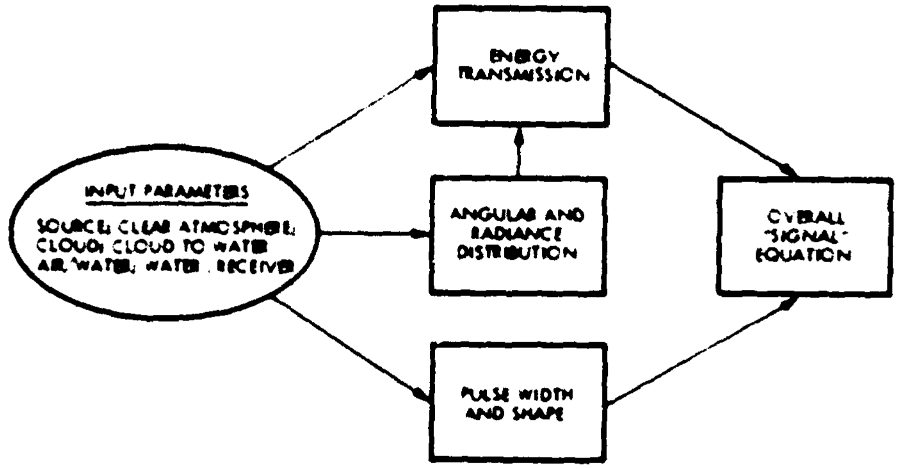

Figure 1-4a. Schematic of "Signal" Single-Pulse Downlink Propagation Model

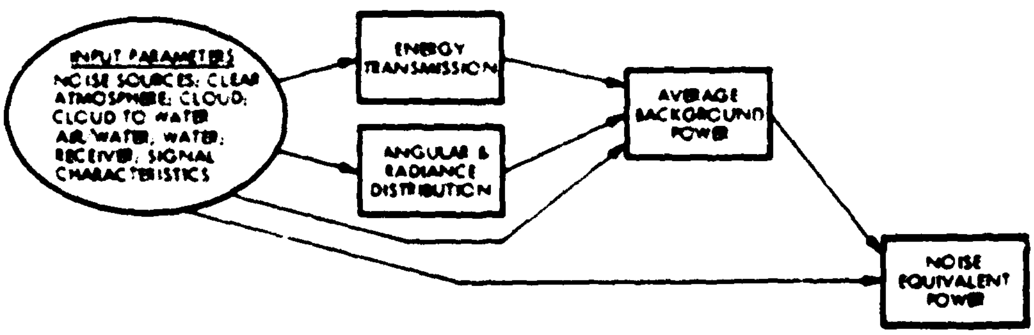

Figure 1-4b. Schematic of Typical Single-Pulse "Noise Equivalent Power" Downlink Propagation Model

1. (Continued)

Section 4.4 presents the computer program for the complete Single Pulse Downlink Propagation Model.

Both Sections 3 and 4 conclude with a discussion of the uncertainties in the present sub-models, and the values of the parameters entering into these sub-models. Key uncertainties include the cloud and water propagation models, and the strength and temporal characteristics of the bioluminescent background.

The Downlink Communication Model (DCM) is derived in Section 5. It considers the problem of communicating one message to a given area during a single time interval while the satellite, sun and moon are each at a single known location, and the environment is specified for all the necessary propagation paths. It includes the effects of laser warm-up time, interframe dead time, time to scan to a new spot, and spot overlap during the scan. It allows for system design choices of modulation format (the number of bits per pulse), demodulation format (threshold or time-of-peak), post detection processing format for anti-jam protection (if time of peak demodulation is chosen), and scanning approach (non-adapt ve, adaptive for assumed thick cloud zenith angle effects, and fully adaptive).

The model outputs include the downlink availability,* and the number of pulses used to achieve this availability, both during a single time interval. In addition, the satellite prime power and the number of jamming and spoofing events per year are derived.

Section 5 is organized in the same manner as Section 3 and 4. The method of approach used is first described, and then a detailed flow chart showing the interactions between the equations and design decisions is shown. Figure 1-5 is a top-level schematic of this flow chart. (The SPDPM is utilized within the availability block.) The second sub-section defines and discusses all the input information needed to perform the calculations and the third subsection presents detailed derivations of all the DCM sub-models.

Section 5.4 presents the computer program for the complete Downlink Communication Model.

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* In this context, downlink availability is defined as that fraction of the allocated area to which the message can be successfully transmitted within the required time interval.

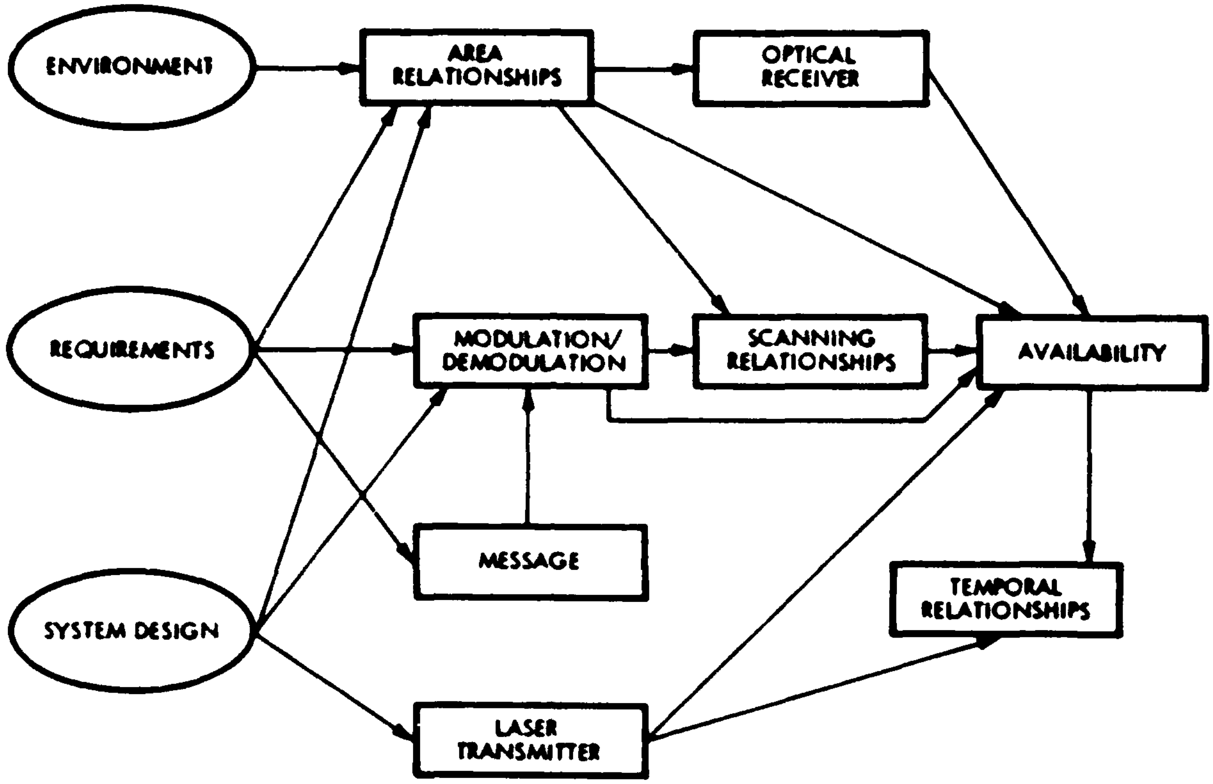

Figure 1-5. Schematic of Downlink Communication Model

1. (Continued)

Section 5 concludes with a discussion of the uncertainties in the sub-models used, and the values of the parameters entering into these sub-models. There are negligible uncertainties in the models, and the key area of uncertainty involves the values of the cloud parameters which apply during a single time interval.

The architecture for the Full OSCAR System Model (FOSM) is derived in Section 6. It considers the problem of communicating three types of messages to the complete required coverage area over a long time (normally, one year). Therefore, the time evolution of the environmental inputs is included, all requirements are treated (including system effectiveness), and the complete system design is used including the ground stations, the uplink, and the full satellite constellation.

The model outputs the system effectiveness for a given system design, with enough intermediate steps to indicate those aspects of system design which are driving the system performance.

1. (Continued)

Section 6 is organized in the same manner as Sections 3, 4, and 5. The method of approach is first described, and then a flow chart showing the interactions between the models and design decisions is shown. Figure 1-6 is a top-level schematic of this flow chart. (The DCM is utilized within the "Downlink Performance, Single Time Interval" block.) The second sub-section defines and discusses all the input information needed to perform the calculations and the third sub-section presents detailed derivations of all the FOSM submodels.

Section 6.4 presents our approach toward implementations of the FOSM. The architecture is completed (as called for in the Statement of Work) and this section discusses the exemplary results to be derived with this architecture.

The section concludes with a discussion of the uncertainties in the analysis, and the values of the parameters entering into the FOSM. The analysis is uncertain, and may be revised in the future, in the areas of system effectiveness formulation, and remote sensor performance. The parameters for the cloud and water data bases are uncertain in both their magnitude, their spectral correlation and their temporal evolution, and should undergo future revision.

Volume IV uses these models to define an OSCAR system able to meet the full requiremetns, for the environment as presently characterized.

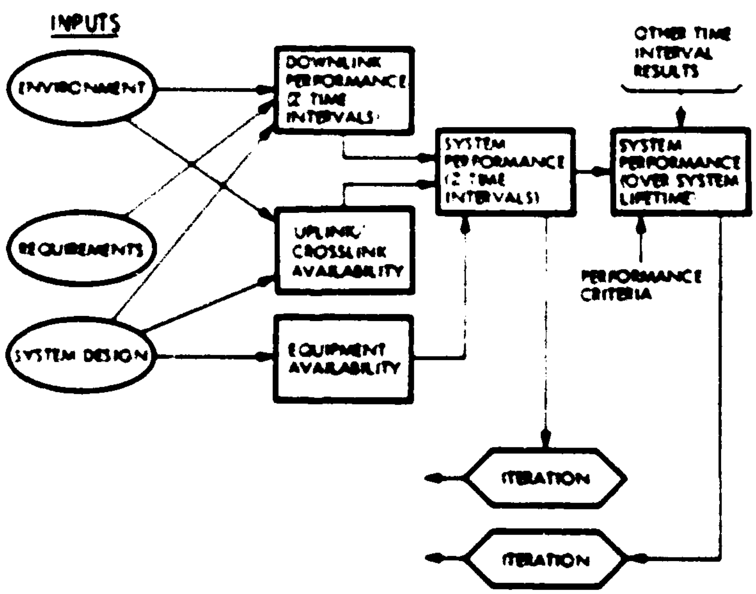

Figure 1-6. Schematic of Full OSCAR System Model

Section 2

GLOSSARY

This section defines all the English and Greek symbols used in the models developed in Sections 3, 4, 5 and 6. The English symbols are listed alphabetically in Subsection 2.1 and the Greek symbols are listed alphabetically in Subsection 2.2.

2.1 ENGLISH SYMBOLS

a = semi-major axis

A_{CL} = crosslink availability

A_{DL} = downlink availability

A_{E} = energy to instantaneous power normalization parameter

A_{GS} = ground station availability

A_{I} = single satellite/single time interval coverage area responsibility

A_{RCT} = area of rectangle within the ellipse

$A_{RCTijMIN}$ = minimum useful spot area in i j resolution element for elliptical spots.

A_{RE} = area of an environmental resolution element

A_{REij} = area of ij resolution element

A_{SAT} = satellite availability

A_{SB} = submarine receiver availability

A_{SC} = area of useful coverage within the spot, for square in circle pattern

A_{SCij} = useful spot area in ij resolution element

A_{SCMIN} = minimum useful spot area

A_{SP} = area of illuminated spot, to exp-2 irradiance points

A_{UL} = uplink availability

A_{UNVL} = system unavailability based on area for which FOM ij <1

A_{VL} = area-based system availability

b = effective clear atmosphere optical thickness

B = electrical detection bandwidth

B_{B} = # of bits to be transferred on the backlink

B_{C} = # of bits to be transferred on the crosslink

B_{OPT} = receiver optical filter bandpass

2.1 (Continued)

B_U = # of bits to be transferred on the uplink

c = speed of light

C_f = fraction of sea-surface covered by foam and streaks

d = diameter of receiver aperture

D = receiver depth

DCM = downlink communication model

D_G = ground station RF antenna diameter

D_i = thickness of i'th water layer

D_{OCij} = mean ocean depth of ij'th ERE

D_S = satellite RF antenna diameter

D_{SP} = diameter of illuminated spot atop water, to exp-2 irradiance points

D_{SPMIN} = minimum spot diameter

D_{SQ} = edge length of square inscribed within the illuminated circular spot

e = charge on the electron

E = eccentric anamoly

E_2 = exponential integral

E_{ff} (SYST) = system effectiveness

E_p = transmitter energy per pulse per terminal

E_{PTOT} = total transmitter energy per pulse

E_R = total received energy per pulse

ERE = environmental resolution element

E_{RF} = RF energy per message bit

exp = exponential

2.1 (Continued)

F = amplifier noise figure

f' (θ_0, θ_R) = fraction of incident radiance within receiver field of view

f' (θ_0, θ_R, θ_{su}) = fraction of incident radiance within receiver field of view

f_a = atmospheric contribution to received beam radiance

f_{cw} = air-water interface contribution to received beam half-angle

f_L = "wall-plug" source efficiency

FOM_{ij} = figure of merit for the ij resolution element, which is the ratio of the achieved signal to noise ratio to the required signal to noise ratio

FOM_{ss} = smallest FOM_{ij} for θopt=50, throughout the coverage area

f(t) = received pulse shape

f_w = water contribution to received beam half-angle

f_{wi} = contribution of i'th water layer to received beam half angle

g = "cost" of jam/spoof system, relative to OSCAR

G = detection gain

G_{AZ} = receiver azimuth pointing angle, relative to local longitude

G_{AZij} = receiver azimuth pointing angle in the ij resolution element

G_{EL} = receiver zenith pointing angle

G_{ELij} = receiver zenith pointing angle in the ij resolution element

G_R = RF antenna gain

H = distance from cloud base to water surface

h = energy per signal photon

i = inclination angle

I = peak signal current

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2.1 (Continued)

IC_{ij} = fraction of ij'th ERE which is covered by ice

I_d = dark current at the photo-cathode

I_n = RMS noise current

I_t = threshold current

$I(\omega^W)$ = water radiance distribution

j = number of water layers present from surface to submarine receiver

J = jammer noise power

k = diffuse attenuation coefficient of the water

k_i = diffuse attenuation coefficient of i'th water layer

(kt) = thermal noise energy = (Boltzmann's constant) x (absolute temperature)

ℓ = number of bits per pulse

L_B = clear sky exo-atmospheric effective radiance due to blue skylight

L_{BL} = spectral irradiance at receiver aperture due to bioluminescence

L_{BS} = spectral radiance at receiver aperture due to blue skylight

L_m = exo-atmospheric effective lunar radiance

L_{MU} = spectral radiance at receiver aperture due to the moon

L_S = exo-atmospheric effective solar radiance

L_{SU} = spectral radiance at receiver aperture due to the sun

L_Z = clear sky exo-atmospheric effective radiance due to stellar and zodiacal light

L_{ZS} = spectral radiance at receiver aperture due to stellar and zodiacal light

m = number of sources or terminals per satellite

MARG = System margin used to compensate for unmodelled noise sources.

M_B = RF margin on the backlink

2.1 (Continued)

M_C = RF margin on the crosslink

M_D = Message length to be delivered, system requirement

M_L = Total message length.

M_{LD} = Message length to be delivered, system requirement

M_{OV} = Overhead bits added to each message

$MTBF_C$ = Mean time between environmental conditions which are sufficient to cause an outage

$MTBF_{SUB}$ = Mean time between failure

$MTTR_C$ = Mean time for outage-causing condition to clear

$MTTR_{SUB}$ = Mean time to repair

M_U = RF margin on the uplink

n = water index of refraction

N_{CC} - Number of crosslinks used in the entire system

NEP_B = Noise equivalent optical power due to shot-noise generated by the background

NEP_{DC} = Noise equivalent optical power due to photo-detector dark current

NEP_{TH} = Noise equivalent optical power due to thermal or amplifier noise

NEP_{SS} = Noise equivalent optical power due to shot-noise generated by the signal

NEP_{TOT} = Total noise equivalent optical power due to all sources

NEP_{TOTij} = Total noise equivalent optical power in the ij resolution element

N_J = Number of jammed messages per year per boat, single pulse processing

N_J' = Number of jammed messages per year per boat, two pulse processing

N_{JI} = Allowed number of jamming messages per year per boat, system requirement

N_M = Number of missed messages per year per boat, system requirement

N_O = Noise power per hertz density at the receiver

2.1 (Continued)

N_{PL} = Total number of pulses used to communicate to the area

N_{Si} = Number of signal pulses received in T_A

${}_{sp}N_{Si}$ = Number of jam/spoof pulses received in T_A

N_{SP} = Number of spoofed messages per year per boat

N_{SP1} = Allowed number of spoofed messages per year per boat, system requirement

N_{SRE} = Number of spots within a resolution element

N_{SREij} = Number of spots in the ij resolution element

N_{SREMAX} = Maximum number of spots within a resolution element

N_{TOTRE} = Number of resolution elements within the area of responsibility

N_{TOTSP} = Total number of spots within this coverage area

$N_{TOTSPMAX}$ = Maximum number of spots required to cover the area of responsibility

P_i = Probability of a jam/spoof pulse occuring in any time slot

P_{AV} = Average power of a single terminal

P_{BS} = Average optical power at receiver due to the blue sky

P_{BL} = Average optical power at receiver due to bioluminescence

P_E = Bit error probability

P_{EN} = Penalty time for a link outage

P_F = Probability that a single threat pulse occurs in an unoccupied slot

P_{2F} = Probability that two threat pulses occur in a given frame

P_{FS} = Probability of false signature, in time-of-peak demodulation

P_{FA} = Single Pulse probability of a false alarm

P_B = Ground station transmitter power

$\dot{P}_{RO}$ = Prime power on the satellite required for all non-laser functions

P_J = Jamming probability, single pulse processing

P_J' = Jamming probability for two pulse processing

2.1 (Continued)

P_{MU} = Average optical power at receiver due to the moon

P_{J1} = Probability of at least one extra pulse occurring in the M_L/k frames

$(P_J G_J)$ = Effective radiated jammer power

P_L = Total prime power (in the satellite) required to sustain the laser sources

P_M = Probability of a missed message

P_N = Probability of a noise spike within one of 2^k-1 slots

PPM = Pulse position modulation

P_R = Peak received signal power

PRF = Pulse repetition frequency of the transmitter

P_{Rij} = Peak received optical power in the ij resolution element

$P_R(t)$ = Instantaneous received signal power

P_S = Satellite transmitter power

P_{Sp} = Spoof probability

P_{SU} = Average optical power at receiver due to the sun

P_{TOT} = Total prime-power capability required on the satellite

P_Z = Average optical power at receiver due to stellar and zodiacal light

q = Parameter describing ability of satellite transmitter to correct for zenith angle spot spreading. $0 \leq q \leq 1$

R = Range from satellite to submarine

R_E = Mean earth radius

R_{GJ} = Range from jammer to the ground station

R_{GS} = Range from ground station to the satellite

R_{ij} = Range from satellite to boat located at α_i, β_j

R_{ijMAX} = Maximum range within the assigned coverage area

R_{JS} = Distance from jammer to satellite

2.1 (Continued)

R_L = Load resistance

R_{MU} = Moon altitude

$\dot{R}_S$ = Satellite altitude

R_S = Rate of change of satellite altitude

R_{SJ} = Distance between 2 satellites

R_{SU} = Sun altitude

$R(\theta_s)$ = Sea-surface reflectance

s = water scattering coefficient

s_i = scattering coefficient of i'th water layer

SPDPM = Single pulse downlink propagation model

$\frac{S}{N})$ = Signal to noise ratio

$\frac{S}{N})_{ij}$ = Signal to noise ratio achieved in the ij resolution element

$\frac{S}{N})_{REQ}$ = Required signal to noise ratio, throughout the coverage area

S_{RF} = RF signal power at the receiver

S_T = Parameter describing area allocated

t = time

T = geometrical thickness of the cloud

T_A = time allowed to cover the allocated area, system requirement

t_{ARV} = adjacent spot revisit time

t_f = dead time between frames

t_{ij} = time to cover the ij resolution element

t_m = time after pulse start at which peak value occurs

T_{NR} = threshold to noise ratio

2.1 (Continued)

T_{ON} = Total source on time for a single coverage time

$T_{o,t}$ = time to cover resolution element for which T_{PART} changes from $<T_A$ to $>T_A$

T_{PART} = time to cover the resolution elements with $FOM_{ij} > 1$, from largest FOM to smallest

t_s = Slot width

$t_{s\ell}$ = dead time between messages, or time to scan to a new spot and to develop the appropriate beam width

T_{sp} = Time devoted to each spot, including slewing time

T_{TOT} = time required to cover the allocated area

$T_{TOT\ MAX}$ = Maximum time required to illuminate the total allocated area

t_w = source turn-on/warm-up time

Δt_c = pulse width due to cloud portion of the path

Δt_{cw} = pulse width due to cloud to water portion of the path

Δt_w = pulse width due to water portion of the path

t = time of day at Greenwich (0° longitude) (Sect. 6.3)

T_{AV} = time over which availabilities are averaged in order to obtain E_{ff} (SYST)

t_B = time allowed to complete backlink

t_C = time allowed to complete crosslink

t_{mo} = time after full moon

t_{nm} = time after sunset

T_{ORB} = Period of the orbit

t_p = time when perigee of the orbit was traversed

t_u = Time allowed to complete uplink

T_{EARTH} = Earth noise temperature

$TECH_{FOM}$ = technology figure of merit

2.1 (Continued)

T_{RAIN} = rain noise temperature

$T_{RECEIVER}$ = Receiver noise temperature

T_{SUN} = sun noise temperature

V = Surface wind speed

V_M = Maximum submarine velocity during communication time, system requirement

w = Number of additional pulses added to message to meet quality of service requirements of time-of-peak demodulation approach

W = Extent of spread spectrum

X_E = receiver coordinate in earth-centered system

X_{MU} = lunar coordinate in earth-centered system

X_S = satellite coordinate in earth-centered system

X_{SU} = solar coordinate in earth centered system

Y_E = receiver coordinate in earth-centered system

Y_{MU} = lunar coordinate in earth-centered system

Y_S = satellite coordinate in earth-centered system

Y_{SU} = solar coordinate in earth-centered system

Z_E = receiver coordinate in earth-centered system

Z_{MU} = lunar coordinate in earth-centered system

Z_S = satellite coordinate in earth-centered system

Z_{SU} = solar coordinate in earth-centered system

2.2 GREEK SYMBOLS

The Greek symbols are listed in order according to the Greek alphabet: α, β, γ, δ, ϵ, ζ, η, θ, ι, κ, λ, μ, ν, ξ, o, π, ρ, σ, τ, υ, ϕ, χ, ψ, ω.

α α_{A_i} = latitude of a point within the coverage area

α_{GS} = latitude of ground station

α_i = mean latitude value for all i resolution elements

α_J = latitude of jammer

α_{MU} = lunar latitude

α_{pm} = phase of the moon

α_S = satellite latitude

α_{SU} = solar latitude

α_{SUB} = latitude of submarine receiver

$\dot{\alpha}_S$ = rate of change of satellite latitude

β β_{A_j} = longitude of a point within the coverage area

β_{GS} = longitude of ground station

β_j = mean longitude value for all j resolution elements

β_J = longitude of jammer

β_{MU} = lunar longitude

β_o = lunar longitude at sunset of a given day

β_S = satellite longitude

β_{SU} = solar longitude

$\dot{\beta}_S$ = rate of change of satellite longitude

β_{SUB} = longitude of submarine receiver

γ γ_T = transmitter optics transmission

γ_R = receiver optics transmission

2.2 (Continued)

δ δ = offset angle between receiver optical axis and axis of the incoming light

δ_{BRij} = in water angle between receiver axis and effective blue-sky direction

δ_{MURij} = in water angle between receiver axis and lunar direction

δ_{SRij} = in water angle between receiver axis and signal direction

δ_{SURij} = in water angle between receiver axis and solar direction

δ_{ZRij} = in water angle between receiver axis and zodiacal/starlight direction

ϵ ϵ = spot overlap factor

ϵ_e = eccentricity of (orbital) ellipse

η η_G = ground station RF antenna efficiency

η_S = satellite RF antenna efficiency

θ θ = cloud particle mean scattering angle

$\langle\cos\theta\rangle$ = mean cosine of the in-cloud scattering angle

θ_T = Full angle exp (-2) transmitter beamwidth

$\Delta\theta_{AW}$ = rms half-angle additional signal beam divergence due to wave action

θ^2_{S1} = Mean square single scattering angle in water

θ^2_{S1i} = Mean square single scattering angle in water for i'th water layer

θ_R = Half angle of the receiver field of view

$\Delta\theta^{SU}_{AW}$ = rms half-angle air-water interface induced spread for the sunlight

$\Delta\theta^{MU}_{AW}$ = rms half-angle air-water interface induced spread for the moonlight

$\theta_{S/2}$ = Half the angle subtended by the sun

$\theta_{M/2}$ = Half the angle subtended by the moon

$\Delta\theta^{B}_{AW}$ = rms half-angle air-water interface induced spread for the blue sky light

$\Delta\theta^{Z}_{AW}$ = rms half-angle air-water interface induced spread for the stellar/zodiacal light

2.2 (Continued)

θ_{TMIN} = Minimum transmitter beam divergence

θ_{TS} = RMS short term satellite pointing jitter

θ_{TDR} = RMS long term satellite pointing drift

θ_{T1} = Minimum transmitter beam divergence from all constraints

θ_{T2} = Transmitter beam divergence for temporal availability in non-adaptive scan

θ_{T1j} = Initial transmitter beam divergence to ij resolution element for partially adaptive scan, or final beam divergence in fully adaptive scan

θ_{T2ij} = Transmitter beam divergence for temporal availability in partially adaptive scan

θ_{SLEW} = Angle between 2 points on the earth's surface, viewed from a satellite

θ_S = Zenith angle from inertially oriented satellite to a point on the earth's surface

$\dot{\theta}_S$ = Rate of change of θ_S

θ_{SA} = Azimuth angle from inertially oriented satellite to a point on the earth's surface

$\dot{\theta}_{SA}$ = Rate of change of θ_{SA}

λ = Optical wavelength

$\Delta\lambda$ = Wavelength shift

$\Delta\lambda_{MIN}$ = Maximum useful bandwidth of optical filter

λ_{RF} = Wavelength of RF link

$\left(\frac{\Delta\nu}{\nu}\right)$ = Optical Doppler shift for satellite to earth path

$\left(\frac{\Delta\nu}{\nu}\right)_S$ = Doppler shift between 2 satellites

σ_C = mean extinction coefficient of the cloud

2.2 (Continued)

τ τ_a = Signal clear atmospheric energy transmission

τ_c = Signal cloud energy transmission

τ_{OPT} = Optical thickness of the cloud

τ_{cw} = Signal cloud to water energy transmission

τ_{aw} = Signal total energy transmission of air-water interface

τ_{aw1} = Signal air-water interface energy transmission due to the index of refraction discontinuity

τ_{aw2} = Signal air-water interface energy transmission due to foam anc streaks on the sea surface

τ_w = Signal water energy transmission

τ_a' = Background clear atmospheric energy transmission

τ_{CS}' = Cloud energy transmission of the direct sunlight

τ'_{CM} = Cloud energy transmission of the direct moonlight

τ'_{CB} = Cloud energy transmission of the blue skylight

τ_{CZ}' = Cloud energy transmission of the stellar and zodiacal light

τ_{CW}' = Background cloud to water energy transmission

τ_{AW}' = Total background energy transmission of the air-water interface

τ_{AW1}' = Background air-water interface transmission due to index of refraction discontinuity

τ_{AW2}' = Background air-water interface transmission due to foam and streaks on the sea surface

τ_{AW1S}' = Solar air-water interface transmission due to index of refraction discontinuity

τ_{AW1M}' = Lunar air-water interface transmission due to index of refraction discontinuity

τ_{AW1B}' = Blue-skylight air-water interface transmission due to index of refraction discontinuity

2.2 (Continued)

τ_{AWIZ}' = Stellar and zodiacal light air-water interface transmission due to index of refraction discontinuity

τ_{WSU}' = Solar water energy transmission

τ_{WMU}' = Lunar water energy transmission

τ_{WB}' = Blue sky water energy transmission

τ_{WZ}' = Stellar and zodiacal light water energy transmission

τ_{RAIN} = RF rain attenuation factor

τ_{RADOME} = RF radome attenuation factor

θ_S = Signal in-air zenith angle

θ_S^W = Signal in-water zenith angle

θ_0 = Off-axis angle at which in-water radiance goes to zero

$\theta_{1/2}$ = Half-power angle of the received signal beam radiance

θ_{SU} = Solar in-air zenith angle

θ_{MU} = Lunar in-air zenith angle

θ^W = Angle measured from the axis, or principal ray direction, of the in-water signal radiance

θ_{SU}^W = Solar in-water zenith angle

θ_{MU}^W = Lunar in-water zenith angle

θ_{Sij} = Signal zenith angle to ij resolution element

θ_{SUij} = Solar zenith angle to ij resolution element

θ_{MUij} = Lunar zenith angle to ij resolution element

θ_{SAij} = Signal azimuth angle relative to local longitude in ij resolution element

θ_{SUAij} = Solar azimuth angle relative to local longitude in ij resolution element

2.2 (Continued)

ϕ_{MUAij} = Lunar azimuth angle relative to local longitude in ij resolution element

θ^{W}_{Sij} = Signal in-water zenith angle to ij resolution element

θ^{W}_{SUij} = Solar in-water zenith angle to ij resolution element

θ^{W}_{MUij} = Lunar in-water zenith angle to ij resolution element

$\dot{\theta}_{S}$ = Rate of change of zenith angle

ϕ_{SA} = Azimuth angle

$\dot{\phi}_{SA}$ = Rate of changes of azimuth angle

ϕ_{SLEW} = Angle between 2 satellites viewed from the earth

ψ_{SLEW} = Angle between a satellite and a point on the earth's surface, viewed from another satellite

ω_{o} = Argument of perigee

Ω = Right ascension of ascending mode

ω_{0} = Cloud particle single scatter albedo

Ω_{0} = Full solid angle containing the incoming in-water radiance

ω_{OR} = Rotational rate of the earth

Ω_{R} = solid angle of the receiver

Section 3

SINGLE PULSE DOWNLINK PROPAGATION MODEL - SIGNAL

This section discusses the model for the optical propagation of a single signal pulse from a satellite to a submerged submarine. The section is organized as follows:

3.1 MODEL PHILOSOPHY AND FLOW CHART

This section describes the basic approach used to generate the detailed single pulse downlink propagation model and presents a flow chart showing the interrelationships of the sub-models and their required inputs.

3.1.1 Philosophy of Approach

The model:

(1) Is organized in a modular fashion, so that the effect of each portion of the path is evident. In addition, as further experiments and analyses are undertaken, pieces of the model may be upgraded without requiring extensive modification of the total model;

(2) Considers the following three properties of the signal, and separately models the effects of the propagation path on each:

(a) The energy transmission from the satellite transmitter to the submerged submarine receiver;

(b) The distribution of the signal radiance at the submarine receiver;

(c) The pulse shape and width at the submarine receiver.

These three properties are then combined to yield the instantaneous received optical power at the surface of the photodetector.

(3) Does not attempt to treat all possible cloud conditions. Rather, a break point is established at a minimum optical thickness of 10. Below that value one set of sub-models is assumed to apply, while above it a different set applies. In many cases these sub-models do not correspond at τ_{opt} = optical thickness = 10, and so the overall model should only be used for $\tau_{opt} < 10$ and $\tau_{opt} >> 10$. (Future analysis and experiments on the "multiple-forward scattering" region should enable the sub-models to be upgraded, and this inconsistency removed.)

(4) Assumes appropriate simple analytic forms for at-present unknown functions such as the radiance distribution, and pulse shape and width. This enables us to present analytic results (except for the receiver axis offset from the beam axis of the incident radiance), which are an aid to a physical understanding of the overall propagation problem.

3.1.2 Model Flow Chart

A schematic of the overall single pulse signal downlink propagation model is presented in Figure 3-1. Given the input parameters, the pulse width and shape and the angular and radiance distribution are derived. Then using the angular and radiance distribution and the input data the energy transmission of the path is calculated. Finally given the energy transmission and the received pulse shape, the signal (instantaneous received power) is calculated.

Figure 3-2 is a detailed flow diagram showing the calculations that must occur to arrive at the required output.

(I) The input parameters are listed in the seven ellipses on the left hand side of the figure, including source, clear atmosphere, cloud, cloud to water, air/water interface, water and receiver parameters. (The symbols are defined in the glossary in Section 2, and also in the input discussion in Section 3.2).

(II) The calculation equations are represented by the rectangular boxes. Within each box is the symbol for the parameter to be calculated and the equation number (from Section 3.3) for the equation to be used to calculate the parameter. The first quantity calculated is the cloud optical thickness, τ_{OPT}, since this determines the equations to be used to calculate many other parameters. Whenever // appears in a rectangular box, the equation number preceding it refers to $\tau_{OPT} < 10$, while the equation number following it refers to $\tau_{OPT} \geq 10$. Hence, given the value of τ_{OPT} the rest of the models to be used are specifically determined.

(III) The second set of calculations performed are of three types:

(a) Path transmission, including τ_a, τ_c, τ_{cw}, τ_{aw} and τ_w;

(b) Pulse width and shape, including Δt_C, Δt_{CW}, Δt_W and t_M;

(c) Angular and radiance distribution, including f_A, f_{AW}, f_W, ϕ_O and $f(\theta_R, \phi_O, \phi)$.

3.1.2 (Continued)

(V) The path transmission, angular and radiance distribution, source and receiver parameters are then used to calculate the received energy, E_R.

(V) The received energy and pulse width and shape are used to calculate the instantaneous received power $P_R(t)$.

The developed computer program is included with that for the noise sources, and presented in Sectic :.

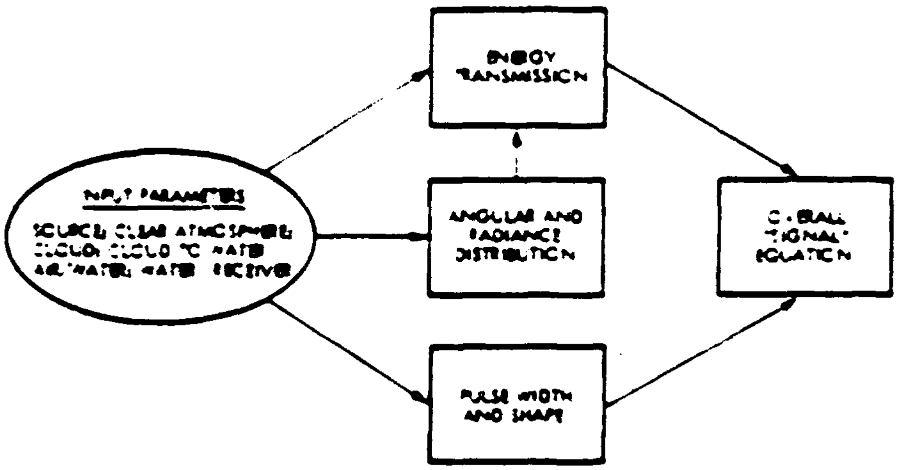


Figure 3-1. Schematic of Signal Single-Pulse Downlink Propagation Model

3.2.3 Cloud

The required parameters are:

Symbol	Description	Units
T	Geometric or physical thickness of the cloud	Meters
σ_C	Average extinction coefficient of the cloud	$(\text{Meters})^{-1}$
q	A parameter describing the ability of the satellite transmitter to correct for the geometric zenith angle spreading of the spot. q = 0 implies the spot remains the same area independent of zenith angle, while q = 1 means the spot grows naturally with zenith angle. Hence $0 \le q \le 1$.	
$\langle\cos\theta\rangle$	The average value of the cosine of the scattering angle for single scattering within the cloud	
θ_s	In-air transmitter zenith angle	Radians
ω_0	The single scattering albedo of the cloud particles, or, the ratio of the probability of scattering to the probability of extinction for a single scattering event.	
θ	The average angle for single scattering within the cloud	Radians

3.2.4 Cloud to Water

The required parameters are:

Symbol	Description	Units
H	Distance from Cloud Base to Water Surface	Meters
R	Range from the satellite transmitter to the submarine receiver	Meters
θ_T	Full angle beam divergence to the e^{-2} irradiance points of transmitted beam	Radians

3.2.5 Air/Water Interface

The required parameters are:

Symbol	Description	Units
θ_S	In-air transmitter zenith angle	Radians
V	Surface wind speed	Meters/Second
n	Water index of refraction	

3.2.6 Water

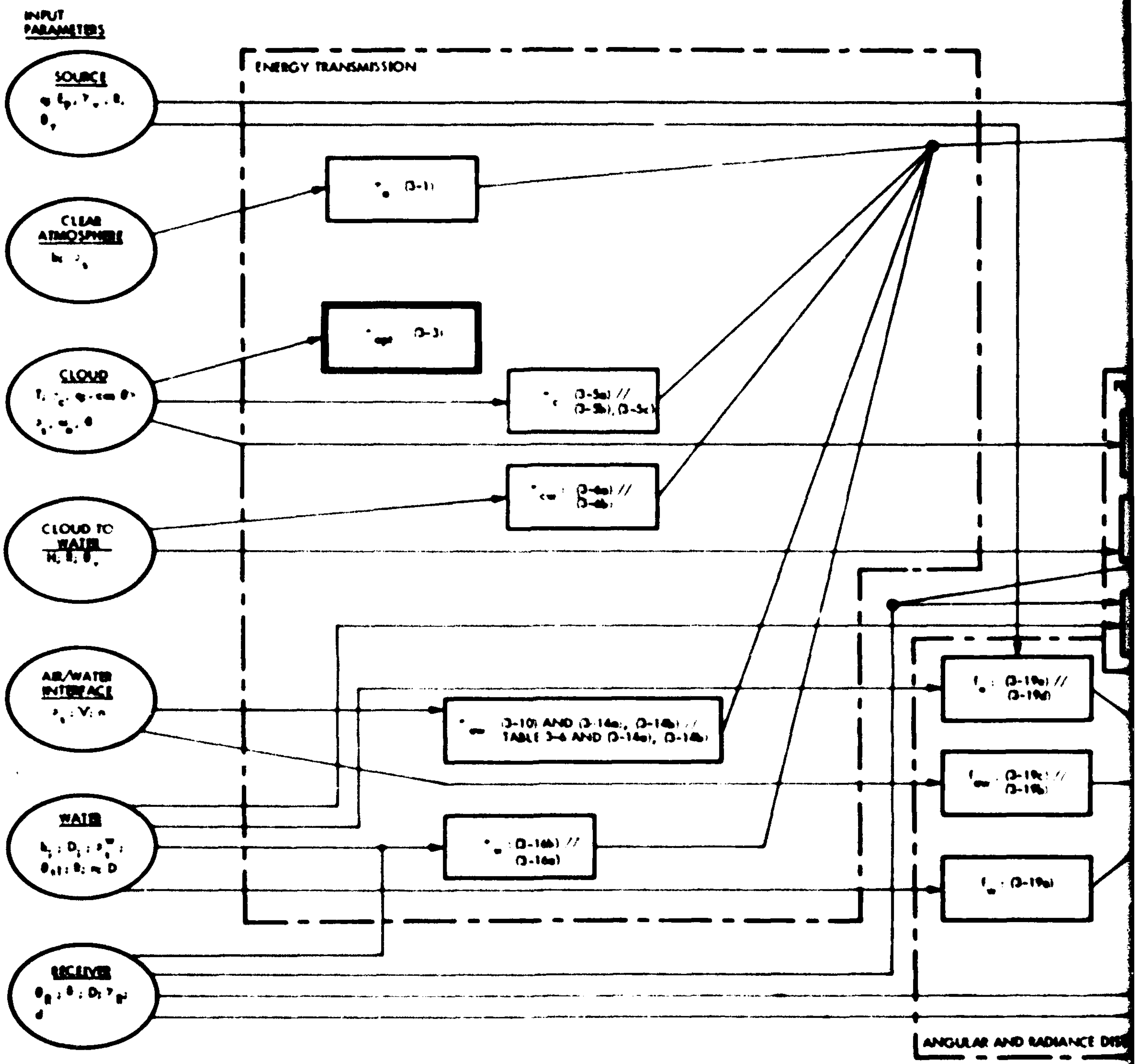
The required parameters are:

Symbol	Description	Units
k_i	Diffuse attenuation coefficient of the i'th water layer	$(\text{Meters})^{-1}$
D_i	Thickness of the i'th water layer	Meters
θ_S^W	In-water transmitter zenith angle	Radians
θ_{SI}	Root-mean-square angle for a single scattering event in the water	Radians
s	Scattering coefficient for the entire water path	$(\text{Meters})^{-1}$
n	Water index of refraction	
D	Depth of the submarine receiver	Meters

3.2.7 Receiver

The required parameters are:

Symbol	Description	Units
θ_R	Half-angle of the receiver field of view	Radians
ϵ	Off-set angle between the in-water signal beam axis and the receiver optical axis	Radians
D	Depth of the submarine receiver	Meters
τ_R	Transmission of the receiver optical chain	
d	Diameter of the receiver optical aperture	Meters



INPUT PARAMETERS
SOURCE
CLEAR ATMOSPHERE
CLOUD
CLOUD TO WATER
AIR/WATER INTERFACE
WATER
RECEIVER
ENERGY TRANSMISSION
(3-1)
(3-3)
(3-5a) // (3-5b), (3-5c)
(3-6a) // (3-6b)
(3-10) AND (3-14a), (3-14b) // TABLE 3-6 AND (3-14a), (3-14b)
(3-16b) // (3-16a)
ANGULAR AND RADIANCE

1

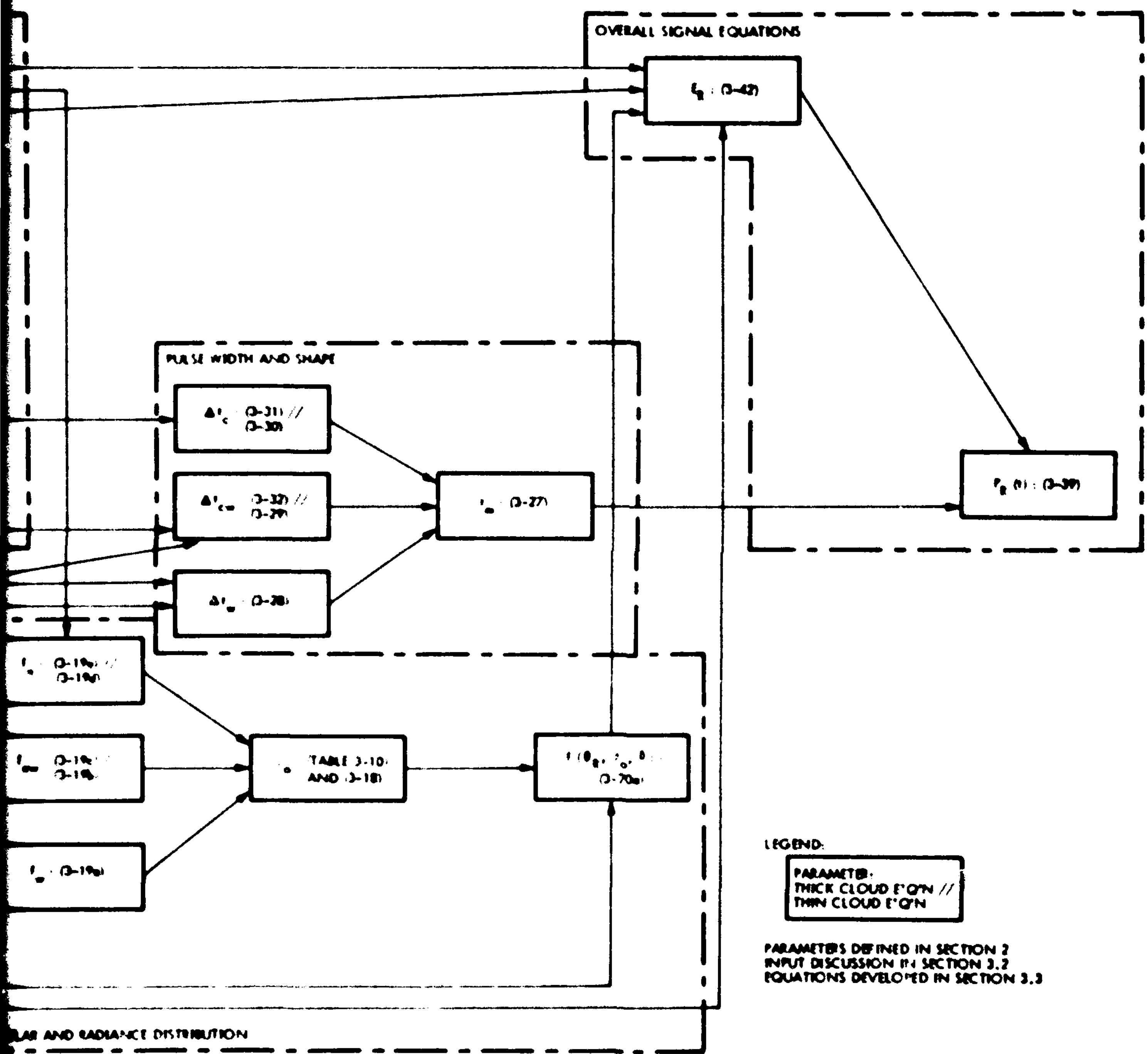


Figure 3-2. Flow Diagram of Single Pulse Downlink Propagation Model (Signal)

2

1

GTE SYLVANIA

3.2 INPUT FOR SIGNAL CALCULATION

This section discusses the form of the required inputs to the signal single pulse downlink propagation model, in terms of the seven categories: source, clear atmosphere, cloud, cloud to water, air/water interface, water and receiver.

3.2.1 Source

The required source parameters are:

Symbol	Description	Units
q	A parameter describing the ability of the satellite transmitter to correct for the geometric zenith angle spreading of the spot. $q = 0$ implies the spot remains the same area, independent of zenith angle, while $q = 1$ means the spot grows naturally with zenith angle. Hence $0 < q \leq 1$.	
E_p	Energy per pulse of the transmitter laser.	Joules
γ_T	Transmission of the transmitter optical chain.	
R	Range from the satellite transmitter to the submarine receiver.	Meters
θ_T	Full angle beam divergence to the e^{-2} irradiance points of the transmitter beam.	Radians

3.2.2 Clear Atmosphere

The required parameters are:

Symbol	Description	Units
b	Effective clear atmosphere optical thickness such that for a 70%-zenith transmission, $b = 0.357$	
ϕ_S	In-air transmitter zenith angle	Radians

3.3 SUB-MODELS

This section develops all the equations used in the calculation of the instantaneous received signal power.

Sections 3.3.1, 3.3.2, 3.3.3, 3.3.4, 3.3.6 and 3.3.7 consider the path transmission of the energy.

Sections 3.3.5 and 3.3.8 consider the angular effects and the distribution of the received radiance.

Section 3.3.9 considers the received pulse shape and width.

In each of these sections, after the equations are developed they are evaluated for typical cases in both tables and figures.

Section 3.3.10 combines the previous results to obtain the received energy and the optical signal power.

GTE SYLVANIA

3.3.1 Clear Atmospheric Transmission - Signal

In the absence of any clouds or aerosols, the clear atmospheric transmission is described by the term τ_a. Using the approximate AFCRL model[1], the signal zenith angle dependence is given by:

$$\tau_a = \exp - (b \sec \theta_s), \tag{3-1}$$

for τ_a = signal clear atmospheric transmission

b = effective clear atmospheric optical thickness

θ_s = signal zenith angle.

The typical value of b is determined from:

$$\tau_a (\theta_s = 0) = 0.7 = \exp (-b),$$

or

$$b = 0.357.$$

Table 3-1 and Figure 3-3 show the values of τ_a as a function of signal zenith angle.

References for Section 3.3.1

1. R.A. McClatchey, R.W. Fenn, J.E.A. Selby, F. E. Volz and J. S. Garing "Optical Properties of the Atmosphere (Revised)" AFCRL-71-0279, 10 May 1971.

Table 3-1. Typical Clear Atmospheric Transmission (b=0.357)

ϕ_s, Signal Zenith Angle (degrees)	τ_a, Clear Atmospheric Transmission
0	0.7
10	0.7
20	0.68
30	0.66
40	0.63
50	0.57
60	0.49
70	0.35
80	0.13

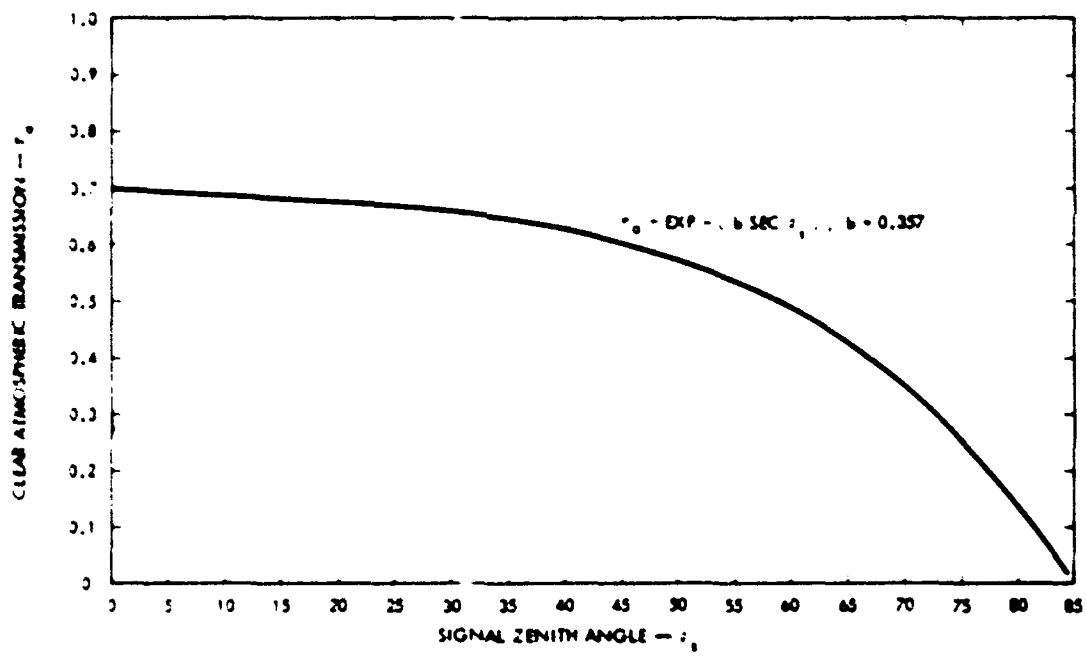


Figure 3-3. Typical Clear Atmospheric Transmission (b = 0.357)

3.3.2 Cloud Energy Transmission-Signal

Insofar as they affect optical propagation, clouds may be categorized as negligible to very thin, thin, and thick. There are no verified experimental results that treat any one of these three regimes. Since we are discussing an energy transmission here, and most analyses and partial experiments are in terms of the transmitted irradiance (energy per second per area), then there are few analytic expressions for the cloud energy transmission.

Our decision is to treat only two regimes - thick clouds and nearly clear weather. We do this with the understanding that evaluating the model near the transition point will yield results that are incorrect in principle, and so only for small and large optical thickness (defined below) should the overall model be expected to apply.

We propose to adopt the multiple-scattering Monte-Carlo derived diffusion-like expression of Bucher[1] and Van der Hulst[2] for thick clouds, so that at zenith, and neglecting in-cloud absorption:

$$\tau_c = \frac{1.69}{\tau_{OPT}\,(1-\langle\cos\theta\rangle) + 1.42} \qquad (3\text{-}2)$$

for τ_c = Signal energy transmission through the cloud

τ_{OPT} = Optical thickness of the cloud

$\langle\cos\theta\rangle$ = Mean cosine of the scattering angle.

The optical thickness of the cloud, for a homogeneous cloud, is given by:

$$\boxed{\tau_{opt} = T\,\sigma_c,} \qquad (3\text{-}3)$$

for

T = geometrical thickness of the cloud,

and σ_c = mean extinction coefficient of the cloud.

For a typical example, for a strato-cumulus cloud, we might have T = 1200 m and σ_c = 0.04 m^{-1} so τ_{opt} = 48. For such a dense cloud, $\langle\cos\theta\rangle \simeq 0.83$ (θ = 34°) and so

3.3.2 (Continued)

$$\tau_c = \frac{1.69}{48\,(1 - 0.83) + 1.42} = 0.18$$

The zenith cloud energy transmission as a function of optical thickness is presented in Table 3-2 and Figure 3-4 for $\langle \cos \theta \rangle = 0.83$

Table 3-2. Typical "Thick" Cloud Zenith Signal Energy Transmission ($\langle \cos \theta \rangle = 0.83$), $\omega_0 = 1$.

τ_{OPT}, Optical Thickness	τ_c, Energy Transmission
10	0.54
20	0.35
30	0.26
40	0.21
50	0.17
60	0.15
70	0.13
80	0.11
90	0.10
100	0.09

From the form of Equation (3-2) it cannot apply at $\tau_{OPT} = 0$, and the lower limit of optical thicknesses at which it does apply is still to be determined. We provisionally adopt a linear fit for $\tau_{OPT} \leq 10$, so that

$$\tau_c = 1 - 0.046\,\tau_{OPT}, \quad \tau_{OPT} \leq 10 \qquad (3\text{-}4)$$
$$\langle \cos \theta \rangle = 0.83$$

Equation (3-4) is evaluated in Table 3-3, and Figure 3-4.

The zenith angle dependence for thick clouds has also been modeled by Bucher[1] and Van der Hulst[2]. It also has no experimental verification.

Table 3-3. "Thin" Cloud Zenith Signal Energy Transmission (Matched to the Thick Cloud Expression at τ_{opt}=10 for $\langle\cos\theta\rangle$ = 0.83)

τ_{opt}, Optical Thickness	τ_c, Energy Transmission
0	1
2	0.91
4	0.82
6	0.72
8	0.63
10	0.54

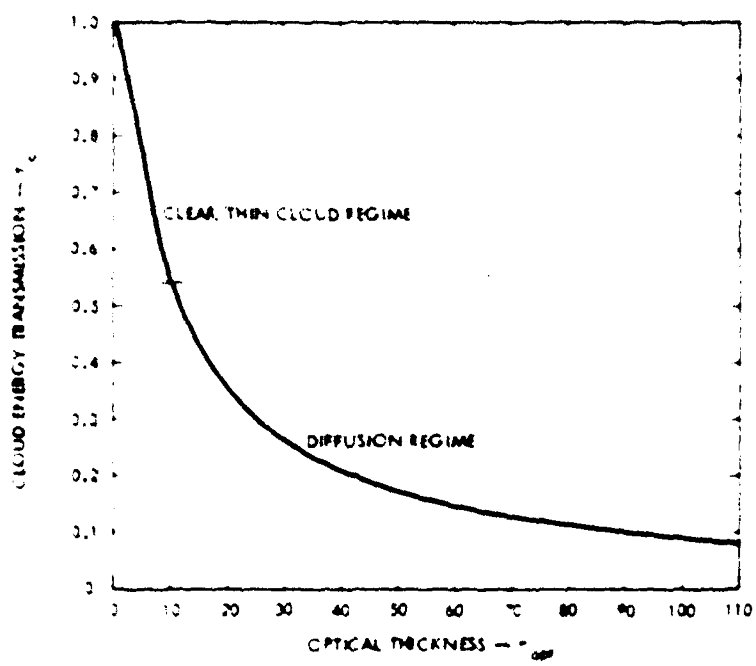


Figure 3-4. Thin and Thick Cloud Energy Transmission Versus Zenith Angles, for $\langle\cos\theta\rangle$ = 0.83, ω_0=1.

3.3.2 (Continued)

The resulting curve has been fit by L. Stotts of NOSC. An additional factor occurs because of the "spreading out" of the beam energy with zenith angle. Since this "spreading out" may be converted to the satellite terminal,* we shall model it as a transmission factor,

$$\left(\cos \theta_s\right)^q \quad , 0 \leq q \leq 1.$$

The complete thick cloud signal energy transmission (including the effects of the single scatter albedo[3], $\omega_0 = 0.999$) is given by:

$$\tau_c = \left\{\frac{1}{\tau_{opt}\,(1-\langle\cos\theta\rangle) + 1.42}\right\} \left\{\cos\theta_s\right\}^q \left\{1.69 - 0.5513\,\theta_s + 2.7173\,\theta_s^2 - 6.9866\,\theta_s^3 + 7.1446\,\theta_s^4 - 3.4249\,\theta_s^5 + 0.6155\,\theta_s^6\right\} \times$$

$$\left\{2\sqrt{3(1-\langle\cos\theta\rangle)\,(1-\omega_0)}\right\} \left\{\tau_{OPT} + \frac{1.42}{1-\langle\cos\theta\rangle}\right\}$$

$$\times \left\{\frac{\exp -\left[\sqrt{3\,(1-\langle\cos\theta\rangle)\,(1-\omega_0)}\,\left\{\tau_{OPT} + \frac{1.42}{1-\langle\cos\theta\rangle}\right\}\right]}{1 - \exp -\left[2\sqrt{3\,(1-\langle\cos\theta\rangle)\,(1-\omega_0)}\,\left\{\tau_{OPT} + \frac{1.42}{1-\langle\cos\theta\rangle}\right\}\right]}\right\} \quad \text{for } 10 \leq \tau_{OPT} \qquad (3\text{-}5a)$$

---

* Except in the unusual condition of a minimum beam size constrained by satellite pointing jitter.

3.3.2 (Continued)

For thin clouds the diffusion like dependence ought not to apply. Therefore, in the $\tau_{OPT} \geq 10$ regime we assume a full cosine dependence due to the extra path length in the cloud, or

$$\tau_c = \left\{ 1 - 0.085\tau_{OPT} \left[\frac{1.69}{10\,(1 - \langle\cos\theta\rangle) + 1.42} \right] \right\} \left[\cos\theta_s\right]^{q+1} \quad \text{for } \tau_{OPT} \geq 10.$$

$$\text{For } \tau_{OPT} = 0, \text{ we use } \tau_c = \left[\cos\theta_s\right]^{q} \qquad (3\text{-}5b)$$

For $\theta_s \neq 0$ these models are discontinuous at $\tau_{OPT} = 10$. The difference in value is approximately a factor of 0.58 at $\theta_s = 70^0$. At this stage in our knowledge of cloud propagation we do not feel that such a factor is of prime importance, and shall ignore this discrepancy until an experimentally verified model replaces it.

Table 3-4 and Figure 3-5 show the zenith angle dependence of the signal energy transmission for both τ_{OPT} regimes, with $q = 0$, i.e., satellite optics fully compensating for the zenith angle beam irradiance spread.

References for Section 3.3.2

1. E.A. Bucher, "Computer Simulation of Light Pulse Propagation for Communication Through Thick Clouds," Applied Optics, Vol. 12 (10), pp. 2391-2400, October 1973.

2. R.E Danielson, D.R. Moore and H.C. Van de Hulst, "The Transfer of Visible Radiation Through Clouds," J. Atmos. Sci. Vol. 26 (9), pp. 1078-1087, September 1969.

3. The effect of $\omega_0 \neq 1$ is taken from Appendix B, equation 14, of S. Karp, "A Test Plan for Determining the Feasibility of Optical Satellite Communications Through Clouds at Visible Frequencies," NOSC TN 279, July1, 1978.

Table 3-4. Zenith Angle vs Signal Energy Transmission (Normalized to $\theta_s = 0$)

θ_s, Signal Zenith Angle	Thick Cloud Dependence ($\tau_{OPT} \geq 10$)	Thin Cloud Dependence ($\tau_{OPT} \leq 10$)
0	1	1
10	0.97	0.98
20	0.96	0.94
30	0.92	0.87
40	0.86	0.77
50	0.78	0.64
60	0.69	0.5
70	0.58	0.34
80	0.44	0.17

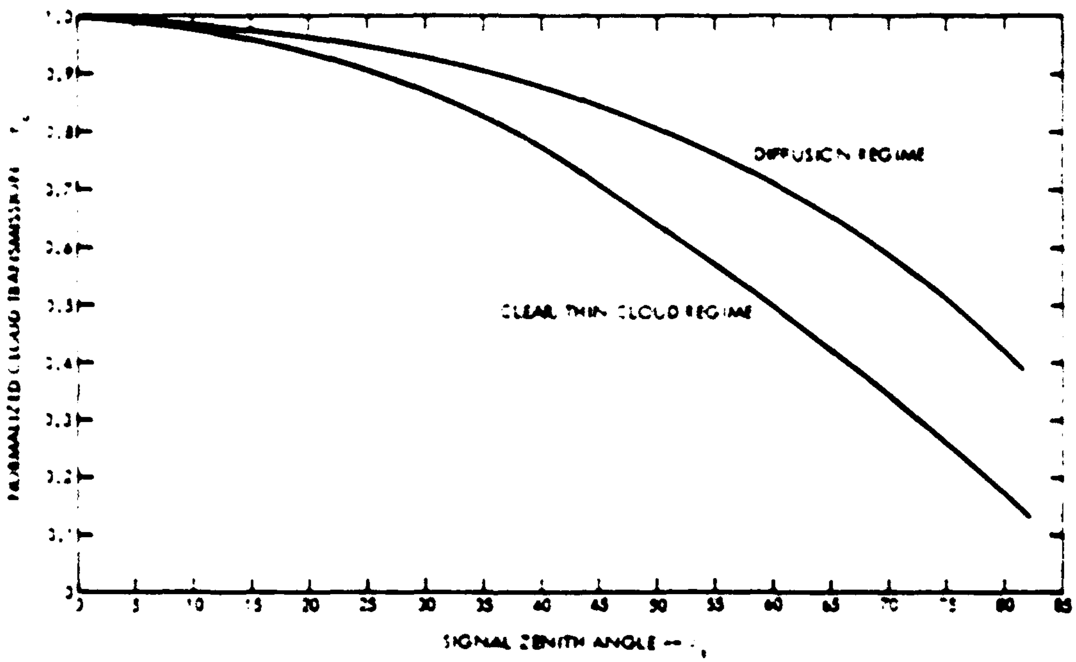


Figure 3-5. Thin and Thick Cloud Zenith Angle Dependence of Cloud Transmission Normalized to Zenith

3.3.3 Cloud to Water Energy Transmission

The energy transmission of an assumed clear propagation path from the bottom of the cloud to the water surface is expressed as τ_{CW}. For large diameter emerging spots and representative clouds the energy transmission of this part of the propagation path is very high.

We consider an area element on the cloud bottom given by $r\,dr\,d\phi$, assuming circular symmetry and that our observation point is well away from the beam edge.

Then, assuming for a thick cloud the emerging energy has a Lambertian distribution, taking

H = distance from cloud base to water

R = range to satellite

θ_T = full angle e^{-2} irradiance beamwidth ($\sim 1^0$) and that the beam is so large at the cloud that negligible additional in-cloud induced spreading occurs, the energy transmission is given by

$$\tau_{CW} = \frac{1}{\pi} \int_0^{2\pi} d\phi \int_0^{R\theta_T/2} r\,dr \quad x \quad (\text{"tilt" of emitting surface area})$$

$$x \; (\text{Range from surface area to water surface "receiver"})^{-2}$$

$$x \; (\text{"tilt" of surface "receiver"}) \quad ,$$

or

$$\tau_{CW} = \frac{1}{\pi} \int_0^{2\pi} d\phi \int_0^{R\theta_T/2} r\,dr \left| \frac{H}{(H^2+r^2)^{\frac{1}{2}}} \right| \left| \frac{1}{(H^2+r^2)^{\frac{1}{2}}} \right|^2 \left| \frac{H}{(H^2+r^2)^{\frac{1}{2}}} \right| ,$$

$$\boxed{\tau_{CW} = 1 - \frac{[H/(R\theta_T/2)]^2}{1 + [H/(R\,\theta_T/2)]^2} \quad , \quad \tau_{OPT} \geq 10} \qquad (3\text{-}6a)$$

Equation (3-6a) is evaluated in Table 3-5 and Figure 3-6 as a function of the ratio of the cloud base height, H, to the emerging spot radius, $R\theta_T/2$.

Table 3-5. Thick Cloud-to-Water Surface Signal Energy Transmission

$H / \frac{R\theta_T}{2}$ $\frac{\text{Cloud Base Height}}{\text{Emerging Spot Radius}}$	τ_{cw}, Energy Transmission
0	1
0.05	0.998
0.1	0.99
0.15	0.98
0.2	0.96
0.25	0.94
0.3	0.92
0.35	0.89
0.4	0.86
0.45	0.83
0.5	0.8

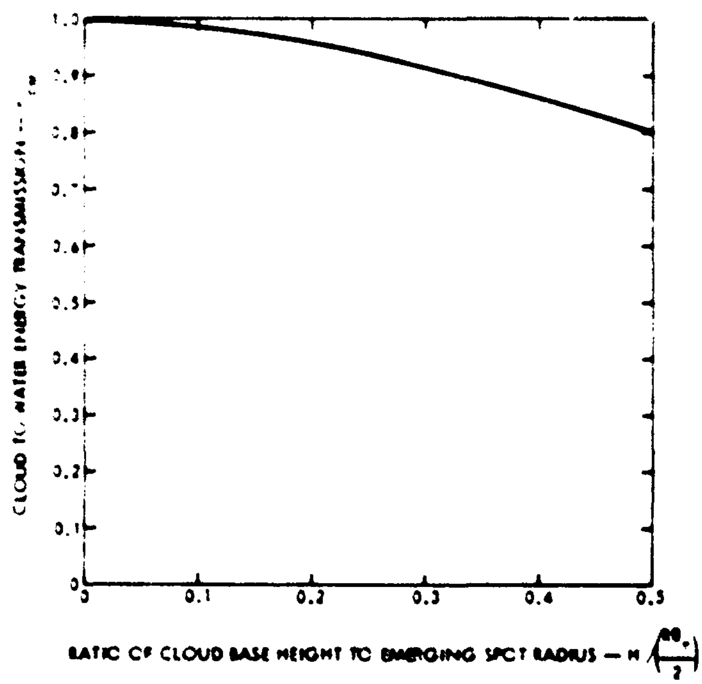


Figure 3-6. Thick Cloud to Water Surface Energy Transmission

3.3.3 (Continued)

For typical situations, $H / \frac{R\theta_T}{2} \lesssim 0.2$ and so this is a very small effect for thick clouds.

For thin clouds, the net transmission is even higher for large incident beams since the energy does retain its emitted angular sense. We therfore take

$$\boxed{\tau_{CW} = 1, \text{ for } \tau_{OPT} \lesssim 10 \quad .} \tag{3-6b}$$

We further assume that there is no zenith angle dependence for τ_{CW} in either regime.

3.3.4 Air-Water Interface Transmission - Signal

The signal energy transmission of the air-water interface is composed of two factors:

$$\tau_{aw} = (\tau_{aw1}) \times (\tau_{aw2}),$$

for τ_{aw} = total energy transmission of air-water interface

τ_{aw1} = air-water interface transmission due to index of refraction discontinuity;

τ_{aw2} = air-water interface transmission due to foam and streaks on the sea surface.

This section treats τ_{aw1} while τ_{aw2} is discussed in Section 3.3.6.

For thin clouds and clear weather ($\tau_{opt} \leq 10$) we assume the signal beam retains its angular sense. Gordon[1] has estimated the value of τ_{aw1} as a function of surface wind speed and signal zenith angle, for the Cox and Munk[2] wave slope distribution, as shown in Table 3-6 and Figure 3-7.

For thick clouds ($\tau_{opt} > 10$), the energy is modelled as being incident on the sea surface from the entire hemisphere. Using the Fresnel refraction equation (and neglecting wave effects) we find

$$\tau_{aw1} = 1 - \int_0^{\pi/2} R(\theta_s) \sin \theta_s \, d\theta_s \qquad (3\text{-}7)$$

for θ_s = signal zenith angle

$R(\theta_s)$ = Sea Surface reflectance as a function of zenith angle,

$$\text{and } R(\theta_s) = \frac{[f_1(\theta_s) - f_2(\theta_s)]\, f_3(\theta_s)}{[f_1(\theta_s) + f_2(\theta_{s1})][f_3(\theta_s) + f_2(\theta_s)]} \qquad (3\text{-}8)$$

$$\text{for } f_1(\theta_s) = \sin^2(\theta_s)\,[n^2 + \cos 2\theta_s] \qquad (3\text{-}9a)$$

$$\text{for } f_2(\theta_s) = \sin \theta_s \sin 2\theta_s \left[n^2 - \sin^2\theta_s\right]^{1/2} \qquad (3\text{-}9b)$$

$$\text{and } f_3(\theta_s) = n^2 \cos^2\theta_s - \sin^2\theta_s \cos 2\theta_s. \qquad (3\text{-}9c)$$

and n = sea-water index of refraction.

Table 3-6. $\bar{\tau}_{awl}$ Time-Averaged Downlink Air-Sea Interface Transmittance (For Thin Clouds, $\bar{\tau}_{opt} \leq 10$)

θ_1 Signal Zenith Angle in Air	V Wind Speed								
	0	1.03	2.06	4.12	7.21	10.3	13.4	16.5	18.6 m/sec
	0	2	4	8	14	20	26	32	38 knots
0	0.979	0.977	0.976	0.974	0.970	0.967	0.963	0.960	0.956
5	0.975	0.974	0.972	0.970	0.966	0.963	0.959	0.956	0.952
10	0.964	0.962	0.961	0.959	0.955	0.951	0.948	0.944	0.941
15	0.945	0.944	0.943	0.940	0.936	0.933	0.929	0.926	0.922
20	0.920	0.918	0.917	0.914	0.910	0.907	0.903	0.899	0.896
25	0.887	0.885	0.884	0.881	0.877	0.873	0.870	0.866	0.863
30	0.847	0.845	0.844	0.841	0.837	0.833	0.829	0.826	0.822
35	0.800	0.798	0.797	0.794	0.790	0.786	0.782	0.779	0.775
40	0.747	0.745	0.743	0.741	0.736	0.733	0.729	0.725	0.722
45	0.687	0.685	0.684	0.681	0.677	0.673	0.669	0.666	0.663
50	0.620	0.619	0.617	0.615	0.611	0.608	0.605	0.602	0.598
55	0.548	0.546	0.545	0.543	0.540	0.538	0.536	0.534	0.532
60	0.469	0.468	0.468	0.466	0.465	0.464	0.464	0.464	0.463
65	0.386	0.385	0.385	0.386	0.387	0.389	0.391	0.393	0.396
70	0.296	0.298	0.299	0.303	0.310	0.315	0.321	0.325	0.329
75	0.203	0.208	0.214	0.224	0.236	0.247	0.255	0.262	0.268
80	0.113	0.126	0.136	0.153	0.172	0.186	0.197	0.206	0.213
85	0.0381	0.0610	0.0751	0.0969	0.119	0.135	0.148	0.157	0.165
90	0	0.0205	0.0390	0.0584	0.0808	0.0961	0.108	0.117	0.124

3.3.4 (Continued)

Using n = 1.33, (3-7) has been evaluated with the result

$$\boxed{\bar{\tau}_{awl} = 0.83, \; \bar{\tau}_{opt} \geq 10.} \qquad (3\text{-}10)$$

Equation (3-10) is an approximation since it has neglected the wave structure of the surface and is discontinuous with the $\bar{\tau}_{opt} \leq 10$ values in Table 3-6. We shall use it pending further analysis and experimentation.

There is no zenith angle dependence for thick clouds for $\bar{\tau}_{awl}$.

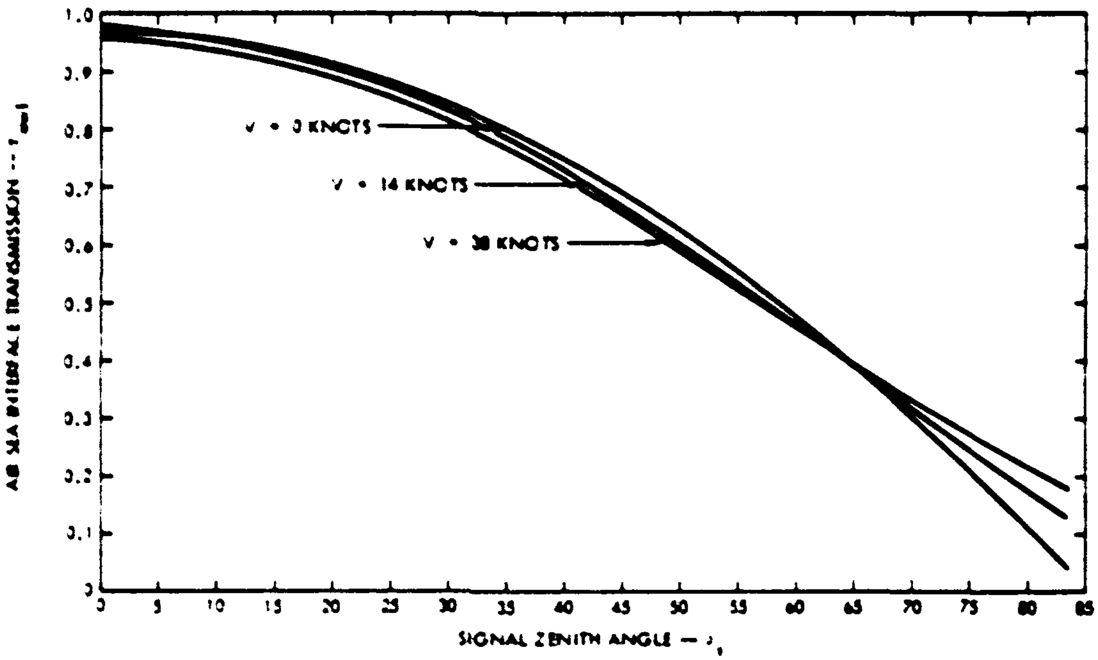


Figure 3-7. Thin Cloud Air-Sea Interface Transmission as a Function of Signal Zenith Angle (θ_s) and Surface Wind Speed, V

3.3.4 (Continued)

References for Section 3.3.4

1. J. Gordon, Directional Radiance (Luminescence) of the Sea Surface, SIO Ref. 89-20, October 1969, as cited in R.E. Howarth, M.E. Hyde and W.R. Stone, "Submarine-Aircraft and Submarine-Satellite Optical Communication Systems Model (U)," Confidential Report, NELC-TR-2021, 1977.
2. C. Cox and W. Munk, "Statistics of the Sea Surface Derived from Sun Glitter, J. Mar. Research Vol 13 2, 1954.

3.3.5 Air-Water Angular Effects - Signal

The wave slopes on the sea surface cause an overall increase in the beam divergence of an incident beam. For the propagation path considered here, only for the thin cloud and clear weather cases ($\tau_{opt} \leq 10$) will this have any effect.

We describe the statistical effects of the surface by $\Delta\theta_{AW}$ = half-angle of the rms additional beam divergence of the radiance profile. Adopting Karp's unverified model[1] we use the expression

$$\boxed{\Delta\theta_{AW} = 0.0103\ V^{1/2}, \quad (\tau_{opt} \leq 10)} \qquad (3\text{-}11a)$$

for V = surface wind speed in knots, and the index of refraction of sea water has been taken = 4/3. Equation (3-11a) is evaluated in Table 3-7 and Figure 3-8 for V in knots (and m/sec) and $\Delta\theta_{AW}$ in radians (and degrees).

The relative contribution of $\Delta\theta_{AW}$ to the distribution of radiance at the receiver will be discussed in Section 3.3.8. Except for the clearest water it is a small effect and so the impact of neglecting zenith angle effects, and dissimilar wave slopes in the downwind and crosswind direction, may be negligible. We therefore adopt this model, and

$$\boxed{\Delta\theta_{AW} = 0, \qquad \tau_{opt} \geq 10} \qquad (3\text{-}11b)$$

until better information is available.

References for Section 3.3.5

1. As cited in R.E. Howarth, M.E. Hyde, and W.R. Stone, "Submarine-Aircraft and Submarine Satellite Optical Communications Systems Model (U)." Confidential Report, NELC-TR-2021, 1977.

Table 3-7. Half-Angle RMS Air-Water Interface Effects

V, Wind Speed		$\Delta\theta_{AW}$	
Knots	Meters/Sec	Milliradians	Degrees
0	0	0	0
2	1.03	14.6	0.84
4	2.06	20.7	1.18
8	4.12	29.2	1.67
14	7.21	38.6	2.21
20	10.3	46.2	2.65
26	13.4	52.6	3.0
32	16.5	58.4	3.35
38	19.6	63.6	3.64

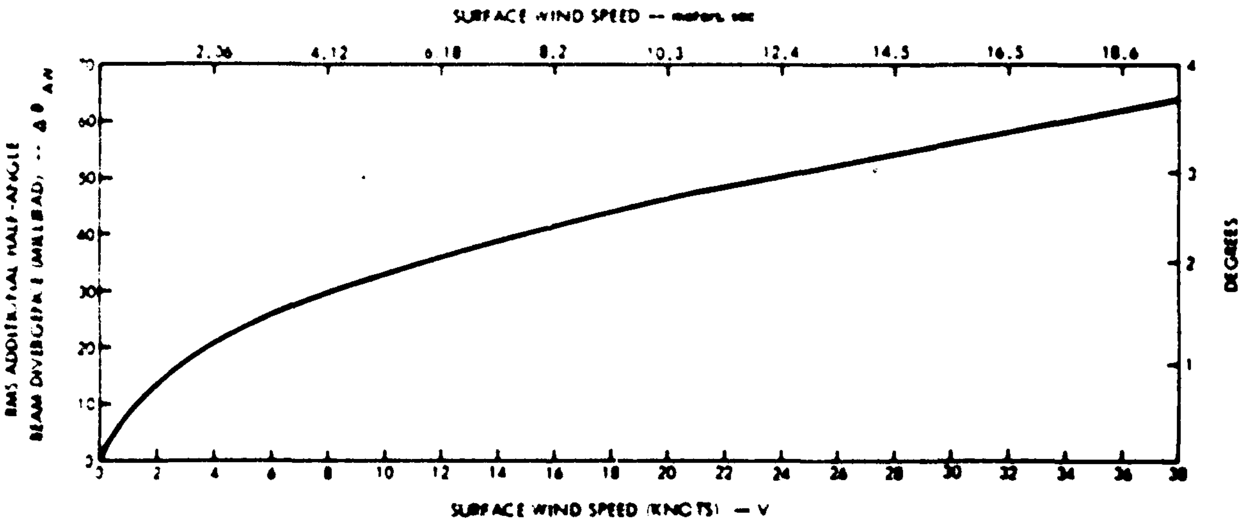


Figure 3-8. Half-Angle RMS Air-Water Interface Effects as a function of Wind Speed V

3.3.6 Relative Surface Foam Coverage

The energy transmission of the air-water interface is composed of the factors:

$$\tau_{aw} = (\tau_{aw\,1}) \times (\tau_{aw\,2}).$$

for τ_{aw} = total energy transmission of the air-water interface

τ_{aw1} = air water interface transmission due to index of refraction discontinuity

and $\tau_{aw\,2}$ = air water interface transmission due to foam and streaks on the water surface.

This section treats $\tau_{aw\,2}$, while $\tau_{aw\,1}$ was discussed in Section 3.3.4. Independent of the cloud conditions, a model relating the fraction of surface covered to the surface wind speed is given by[1]

$$C_f = (1.2 \times 10^{-5})\, V^{3.3}, \quad V \leq 9\text{m/sec} \qquad (3\text{-}12)$$

and $$C_f = (1.2\,(10^{-5})\, V^{3.3}\,(0.225\,V - 0.99); \quad V \geq 9\text{m/sec}, \qquad (3\text{-}13)$$

for C_f = fraction of surface covered

V = surface wind speed in meters/sec.

Assuming the foam and streaks have an albedo of 1, the value of $\tau_{aw\,2}$ is given by:

$$\tau_{aw\,2} = 1 - (1.2\,(10^{-5})\,)\, V^{3.3}, \quad V \leq 9\text{m/sec} \qquad (3\text{-}14a)$$

and $$\tau_{aw\,2} = 1 - (1.2\,(10^{-5}))\, V^{3.3}\,(0.225\,V - 0.99); \quad V \geq 9\text{m/sec} \qquad (3\text{-}14b)$$

Equations (3-14a, b) are evaluated in Table 3-8 and Figure 3-9 for V in meters/sec (and knots).

Although this model neglects zenith angle effects, we shall adopt it pending further experimental work.

References for Section 3.3.6

1. As cited in H.R. Gordon and M.M. Jacobs, "Albedo of the Ocean-Atmospheric System: Influence of the Sea Foam," Appl. Opt. Vol 16 (8) pp 2257-2260, Aug 1977.

Table 3-8. Air-Water Energy Transmission Due to Surface Foam and Streaks (Assuming a foam/streak albedo = 1)

V, Wind Speed		τ_{aw2}
Knots	Meters/Sec	
0	0	1
2	1.03	1
4	2.06	1
8	4.12	1
14	7.21	0.99
20	10.3	0.96
26	13.4	0.87
32	16.5	0.66
38	19.6	0.25

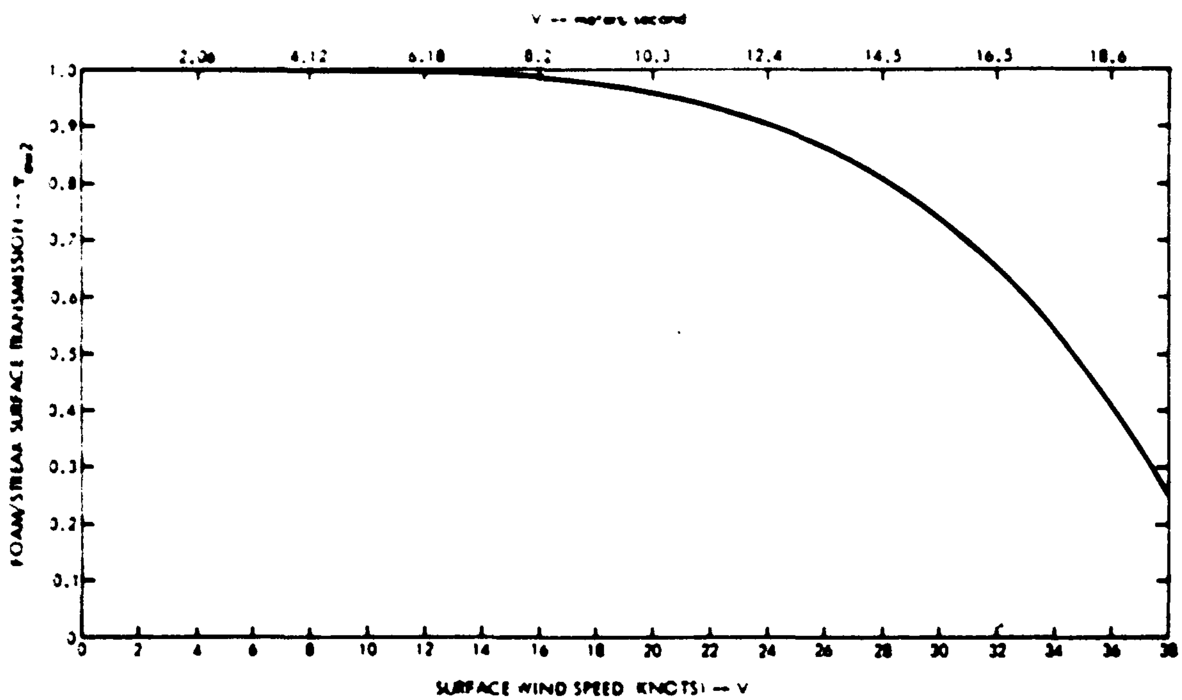


Figure 3-9. Foam/Streak Surface Coverage Transmission versus Surface Wind Speed

3.3.7 Water Energy Transmission-Signal

The energy transmission of the water portion of the propagation path is denoted by τ_w. For most water types and receiver depths the dominant cause of attenuation is the diffuse attenuation coefficient[1] of the water, k. We therefore use the model:

$$\tau_w = \exp - (k \times \text{(PATH LENGTH IN WATER)}).$$

The path length in the water for $\theta_{opt} \leq 10$ is given by:

$$D/\cos(\theta_s^w),$$

for

D = receiver depth

θ_s^w = in water signal zenith angle.

From Snell's law,

$$n \sin(\theta_s^w) = \sin \theta_s, \tag{3-15}$$

for

n = water index of refraction

θ_s = in air signal zenith angle.

Table 3-9 and Figure 3-10 show the values of Equation (3-15) for $n = 1.33$. Since many areas of the ocean have a layered structure for k, we modify our basic equation for clear weather or/thin cloud conditions to yield:

$$\frac{k\,D}{\cos(\theta_s^w)} = \frac{1}{\cos(\theta_s^w)} \sum_{i=1}^{j} (k_i\,D_i),$$

where we have assumed there are j layers which differ in their k values, but not in their indices of refraction. Therefore, the adopted model for $\theta_{opt} \leq 10$ is

Table 3-9. Relation Between In-Air and In-Water Signal Zenith Angles (Assuming Sea-Water Index of Refraction, n = 1.33)

θ_s, In-Air Signal Zenith Angle (Degrees)	θ_s^w, In-Water Signal Zenith Angle (Degrees)
0	0
5	3.75
10	7.48
15	11.19
20	14.86
25	18.48
30	22.02
35	25.48
40	28.82
45	32.03
50	35.07
55	37.91
60	40.51
65	42.82
70	44.81
75	46.42
80	47.61
85	48.34

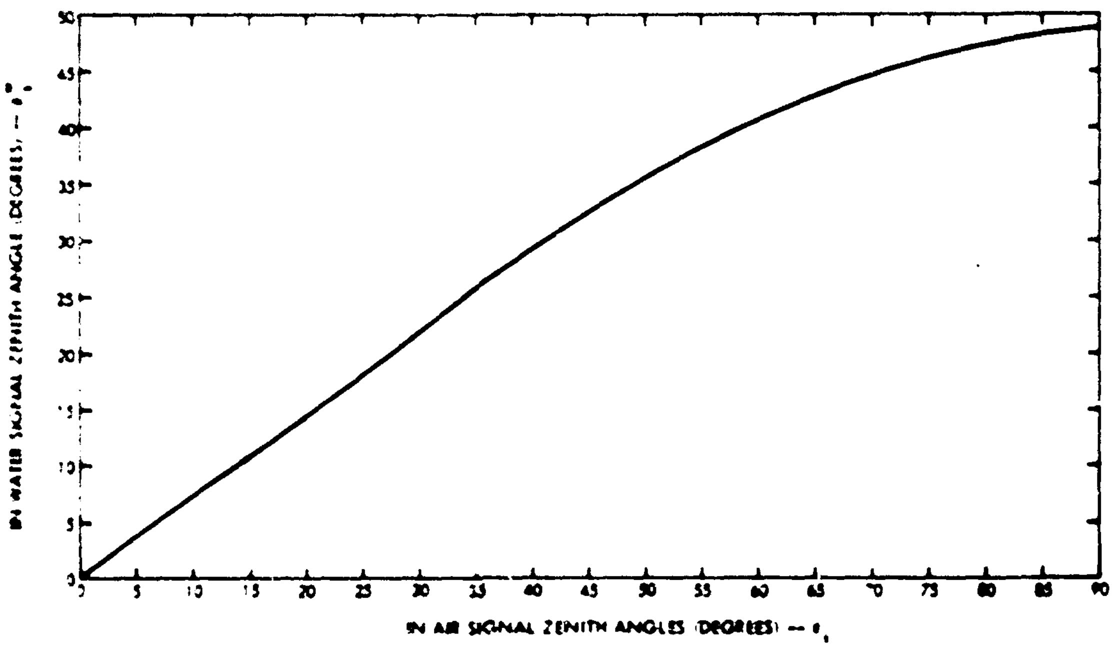


Figure 3-10. Relation Between In-Air and In-Water Signal Zenith Angles (Assuming Sea-Water Index of Refraction, n = 1.33)

3.3.7 (Continued)

$$\tau_w = \exp - \left\{ \frac{\sum_{i=1}^{J} k_i D_i}{\cos \theta_s^w} \right\} \quad , \text{ for } \tau_{opt} \leq 10$$

$$\theta_s^w = \sin^{-1}\left(\frac{1}{n}\sin\theta_s\right) \quad \text{and} \quad \sum_{i=1}^{J} D_i = D \quad . \tag{3-16a}$$

For thick cloud conditions, the energy peaks at zenith. Since k_i is an effective diffusion coefficient, the thick cloud water energy transmission is given by

$$\tau_w = \exp - \left\{ \sum_{i=1}^{J} k_i D_i \right\} \quad , \text{ for } \tau_{OPT} > 10 \tag{3-16b}$$

This model is uncertain in many ways:

(1) The value of k_i to use.

(2) The values of D_i.

(3) Its applicability in very clear water and/or at shallow receiver depths.

Consequently, although it is the best model available now, it may be revised when better information becomes available.

References for Section 3.3.7

1. R.E. Howarth, M.E. Hyde and W.R. Stone, "Submarine Aircraft and Submarine-Satellite Optical Communication Systems Model (U)", Confidential Report, NELC-TR-2021, 1977.
2. M. Abramowitz and I.A. Stegun, editors, Handbook of Mathematical Functions, NBS, Applied Mathematics Series 35, Government Printing Office, November 1970, p. 228,238-243.

3.3.8 Water Distribution of Radiance - Signal

There is no experimentally verified expression for the in-water distribution of signal radiance as a function of incident beam collimation, incident beam zenith angle, water properties, and receiver depth. Any model expression must take into account the following items:

(1) The in-air zenith angle of the signal;
(2) The radiance distribution incident on the water;
(3) The air-water interface effects;
(4) The in-water zenith angle of the signal;
(5) The in-water scattering effects;
(6) The in-water absorption effects.

In considering these last two, we note that the energy should decrease away from zenith due to absorption, and depending on depth and the water properties. We have therefore considered the following zenith angle dependencies for the radiance at the submarine receiver:

(1) Uniform

(2) $$1 - \left(\frac{\theta^w}{\theta_0}\right)$$

(3) $$\frac{\sin\left(\theta_0 - \theta^w\right)}{\sin \theta_0}$$

(4) $$1 - \left[\frac{\sin(\theta^w)}{\sin(\theta_0)}\right]^2$$

(5) $$\exp - \left(\frac{\theta^w}{\theta_0}\right)$$

3.3.6 (Continued)

for θ^w = angle measured from the axis, or principal ray direction, of the in-water signal radiance,

and θ_0 = angle at which the signal radiance reaches a benchmark, i.e. 0 for (2) (3) and (4), and e^{-2} for (5).

We adopt (4), $\left[\dfrac{1-\sin\theta^w}{\sin\theta_0}\right]^2$, because it is easy to work with, and appears to give a reasonable representation of the assumed radiance.

θ_0 is related to the half power point of the received radiance by the equation

$$\frac{1}{2} = \frac{1-\cos\left(\theta_{1/2}\right)-\dfrac{1}{3\sin^2\theta_0}\left[\cos\theta_{1/2}\sin^2\theta_{1/2}+2\cos\theta_{1/2}-2\right]}{1-\cos\theta_0-\dfrac{1}{3\sin^2\theta_0}\left[\cos\theta_0\sin^2\theta_0+2\cos\theta_0-2\right]} \qquad (3\text{-}17)$$

Equation (3-17) is evaluated in Table 3-10. Values between those shown are obtained by linear interpolation.

Table 3-10. Relation of Radiance Zero Point, ϕ_0, and Received Radiance Half-Power Point, $\phi_{1/2}$, for $1 - (\sin \phi^w / \sin \phi_0)^2$ Radiance Distribution

$\phi_{1/2}$ (degrees)	ϕ_0 (degrees)
3.8	5
7.6	10
11.4	15
15.2	20
19.0	25
22.7	30
26.5	35
30.2	40
33.9	45
37.5	50
41.1	55
44.6	60
48.1	65
51.6	70
54.9	75
58.2	80

3.3.8 (Continued)

We adopt the NOSC developed expression for the half-power point in terms of incident beam divergence, air-water angular effects and in-water scattering effects, and add them up as if they were three statistically* independent effects:

$$\boxed{\phi_{1/2} = [f_w + f_{aw} + f_a]^{1/2} .} \qquad (3\text{-}18)$$

for

$$\boxed{\begin{aligned} f_w &= \text{water contribution} \\ &= \frac{\phi_{si}^2 \, s \, D}{\cos \phi_s^w} , \quad \text{all } \tau_{OPT} \end{aligned}} \qquad (3\text{-}19a)$$

*This is actually an empirical result, and appears to fit the NOSC experimental results. A completely consistent theory of all these effects would not use the statistical independence as the justification for this expression.

3.3.8 (Continued)

$$f_{aw} = (0.0103\ V^{1/2})^2; \quad \tau_{OPT} \leq 10 \tag{3-19b}$$

$$= 0 \quad ; \quad \tau_{OPT} \geq 10 \tag{3-19c}$$

and

$$f_a = \left(\frac{1}{n}\right)^2 (0.294\ \theta_T)^2\ ;\ \tau_{OPT} \leq 10; \tag{3-19d}$$

$$= (33.8^0)^2; \quad \tau_{OPT} \geq 10. \tag{3-19e}$$

for θ_s^2 = mean square single scattering angle in water

s = scattering coefficient in water

D = receiver depth

θ_s^w = in-water signal zenith angle.

V = surface wind speed in knots

τ_{OPT} = cloud optical thickness

n = water index of refraction

θ_T = e^{-2} irradiance full angle of in-air incident beam.

Equation 3-19a is the NOSC[1] expresssion, and contains the only zenith angle dependence for the radiance distribution. We could modify it for layering effects ($\theta_{s1} \rightarrow \theta_{s1i}$; $s \rightarrow s_i$; $D \rightarrow D_i$ and $f_w \rightarrow \Sigma_i (f_{wi})$) but shall not at this time, until further experimental results are obtained.

Equations 3-19b and 3-19c are based on the discussion in Section 3.3.5.

Equations 3-19d is the refraction-corrected beam divergence of the collimated incident beam, again assuming a Gaussian distribution in angle.

Equations 3-19e assumes that after penetration through thick clouds the light has a uniform angular distribution at the water surface. Then, Snell's law implies that just below the water surface, all the energy is contained within a solid angle of half-angle = 48.6^0, neglecting wave action. Then, defining the half-power angle as the half-angle of the solid angle containing half of the energy, implies

3.3.8 (Continued)

$$1 - \cos \theta = \frac{1}{2}\,(1 - \cos 48.6^{o})$$

or, $\theta = 33.8^{o}$.

The radiance distribution enters into the expression for the received energy by the expression

$$f\,(\theta_R, \theta_0, \delta) = \frac{\int^{\Omega_R} \left[1 - \left(\dfrac{\sin \theta^{w}}{\sin \theta_0} \right)^2 \right]}{\int \left[1 - \left(\sin \theta^{w} / \sin \theta_0 \right)^2 \right]}$$

for

Ω_R = solid angle of the receiver,

Ω_0 = full solid angle which all the energy is within,

θ_R = half-angle of the receiver field of view,

δ = off-set angle between receiver optical axis and axis of the incoming light.

Therefore, for the general case,

$$f\,(\theta_R, \theta_0, \delta) = \frac{\displaystyle\int_0^{2\pi} d\phi \int_0^{\theta_R} d\theta^{w} \sin \theta^{w} \left[1 - \left(\frac{\sin \theta^{w'}}{\sin \theta_0} \right)^2 \right]}{\displaystyle\int_0^{2\pi} d\phi \int_0^{\theta_0} d\theta^{w} \sin \theta^{w} \left[1 - \left(\frac{\sin \theta^{w}}{\sin \theta_0} \right)^2 \right]} \qquad (3\text{-}20a)$$

for

$$\theta^{w'} = \cos^{-1} \left\{ \cos \theta^{w} \cos \delta + \sin \theta^{w} \sin \delta \sin \phi \right\} .$$

For perfect alignment between the received light axis and the receiver ($\delta = 0$), the integral can be analytically evaluated, with the result

$$f(\theta_R, \theta_0) = \frac{1 - \cos\theta_R - \left(\frac{1}{3\sin^2\theta_0}\right)\left[\cos\theta_R \sin^2\theta_R + 2\cos\theta_R - 2\right]}{1 - \cos\theta_0 - \frac{1}{3\sin^2\theta_0}\left[\cos\theta_0 \sin^2 + 2\cos\theta_0 - 2\right]} \qquad (3\text{-}20b)$$

Equation (3-20a) has been evaluated in Figure 3-11, for $\theta_0 = 30^\circ$ (Figure 3-11a) and $\theta_0 = 70^\circ$ (Figure 3-11a) and $\delta = 0^\circ, 10^\circ, 20^\circ, 30^\circ, 40^\circ, 50^\circ, 60^\circ$.

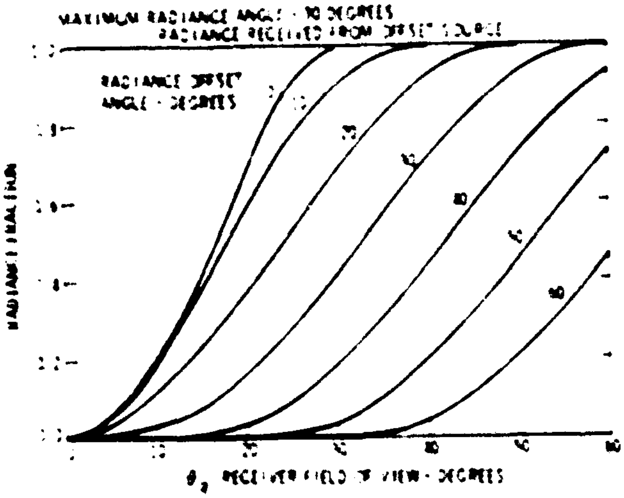


Figure 3-11a $f(\theta_R, \theta_0, \delta)$ for $\theta_0 = 30^\circ$

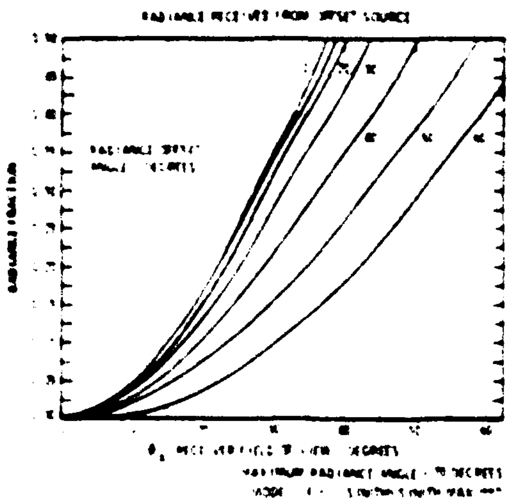


Figure 3-11b $f(\theta_R, \theta_0, \delta)$ for $\theta_0 = 70^\circ$

These results will be used in Section 3.3.10.

3.3.8 (Continued)

References for Section 3.3.8

1. R.E. Howarth, M.E. Hyde and W.R. Stone, "Submarine-Aircraft and Submarine-Satellite Optical Communications Systems Model (U)", Confidential Report, NELC-TR2021, 1977.

3.3.9 Received Pulse Width/Shape

There is no verified model which predicts the received pulse width and shape at the submarine receiver as a function of cloud properties, cloud height above the water, water properties, and the receiver field-of-view. We do not attempt to develop such a final model here, but present some reasonable expressions for the model we propose to temporarily adopt.

It is the universal[1] experience of experimenters (both real-world and computer simulations) that after penetration of a multiple scattering medium, the received pulse has a short rise time and a long falltime. Because of its nearness to Bucher's computer simulations[2] (as shown in Figure 3-12) we shall assume the underwater receiver sees a pulse shape given by

$$\boxed{f(t) = te^{-kt}.} \tag{3-21}$$

The properties of this form are as follows:

Maximum value of $f(t)$ occurs at $t_M = \frac{1}{k}$ (3-22)

Maximum value of $f(t) = t_M e^{-1} = 0.368\ t_M$ (3-23)

Average value of t, defined as

$$\frac{\left(\int_0^\infty t\ f(t)\ dt\right)}{\left(\int_0^\infty f(t)\ dt\right)} = 2\ t_M . \tag{3-24a}$$

Half power points of $f(t)$ occur at $0.233\ t_M$ and $2.68\ t_M$, so the width between half power points $= 2.45\ t_M$. (3-24b)

3.3.9 (Continued)

The rms value of t, defined as

$$\left\{ \frac{\int_0^\infty t^2 f(t)\, dt}{\int_0^\infty f(t)\, dt} \right\}^{1/2} = \sqrt{6}\; t_M . \qquad (3\text{-}24c)$$

Hence the variance of t is given by var $t = (\overline{t^2} - \bar{t}^2) = 2\, t_M^2$. (3-25a)

and its standard deriation by $[\overline{t^2} - \bar{t}^{\,2}]^{1/2} = \sqrt{2}\; t_M$. (3-25b)

The area under the $f(t)$ curve is given by

$$\int_0^\infty f(t)\, dt = t_M^{\,2} . \qquad (3\text{-}26)$$

In principle there are three significant contributions to the received pulse width, which we shall define as the time between half power points,

$$\boxed{2.45\, t_M = (\Delta t_c + \Delta t_{cw} + \Delta t_w) ,} \qquad (3\text{-}27)$$

where we have neglected the initial pulse width at the transmitter, assumed that the effects add serially, not statistically, and

Δt_w = pulse width due to water portion of the path,

Δt_{cw} = additional pulse width due to cloud-to-water path,

Δt_c = pulse width after emerging from the cloud.

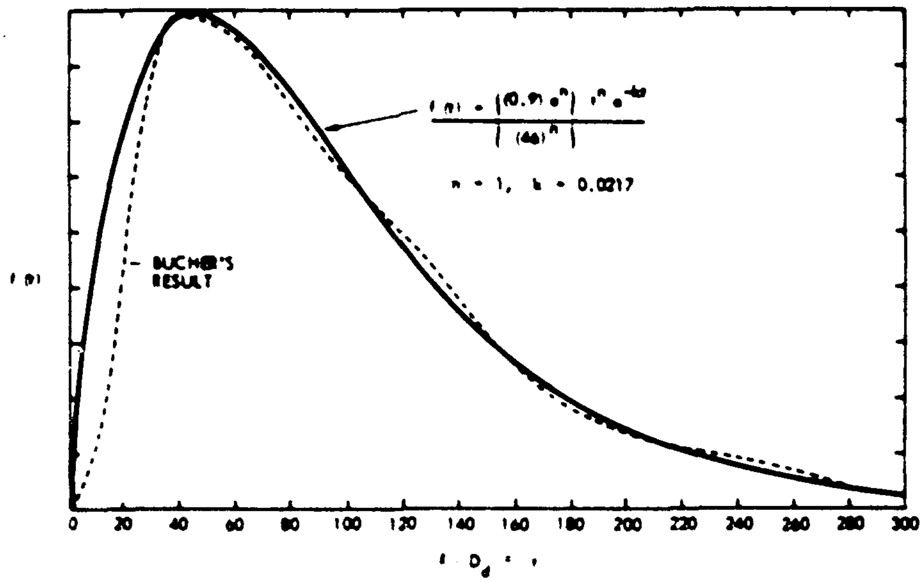


Figure 3-12. Comparison of f(t) and Bucher's Monte Carlo Pulse Shape

3.3.9 (Continued)

The additional pulse width due to the water portion of the path is caused by the in-water multiple scattering, and so it occurs in the absence or presence of clouds. As seen in Figure 3-13, a signal at a zenith angle of 0° and a receiver of half angle θ_R at a depth D leads to a pulse width (for a uniform contribution throughout that field of view)

$$\boxed{\Delta t_w = \frac{D}{c/n}\left(\frac{1-\cos\theta_R}{\cos\theta_R}\right), \text{ all } \theta_{opt}} \tag{3-28}$$

for c = speed of light

n = water index of refraction.

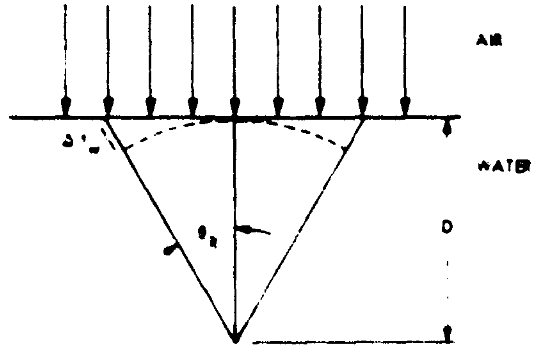


Figure 3-13. In-Water Pulse Width Calculation Geometry

3.3.9 (Continued)

When the signal zenith angle is not 0°, an additional pulse stretching occurs, as shown in Figure 3-14. The effect is given by

$$\boxed{\Delta t_{cw} \simeq \frac{2\,D \tan \theta_R \sin \theta_s}{c}, \qquad \tau_{opt} \geq 10} \qquad (3\text{-}29)$$

for θ_s = signal zenith angle.

When thick clouds are in the path, there is no single zenith angle defined below the clouds, and so this expression will not apply.

For thin clouds ($\tau_{opt} \leq 10$) we have found no verified expression for the cloud effects or the cloud to water effects. Since Equations (3-28) and (3-29) already imply stretching to a few hundred nanoseconds, we can neglect the thin cloud effects, and take

$$\boxed{\begin{array}{c}\Delta t_c = 0, \qquad \tau_{opt} \leq 10 \; . \\ \text{All zenith angles}\end{array}} \qquad (3\text{-}30)$$

For thick clouds we adopt the Stotts[3] expression, (applicable for $\omega_0 > 0.999$) so that:

$$\boxed{\begin{array}{c}\Delta t_c = \frac{T}{c}\left\{\frac{0.3}{\omega_0\,\tau_{opt}\,\theta^2}\left[\left(1 + 2.25\,\omega_0\,\tau_{opt}\,\theta^2\right)^{1.5} - 1\right] - 1\right\}, \quad \tau_{opt} \geq 10 \; . \\ \text{All zenith angles}\end{array}} \qquad (3\text{-}31)$$

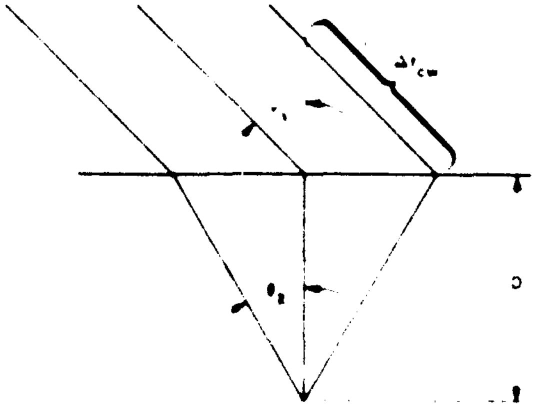


Figure 3-14. Signal Zenith Angle Induced Additional Pulse Stretching

3.3.9 (Continued)

for T = cloud geometrical thickness,

ω_0 = single scatter albedo,

θ = mean scattering angle in the cloud.

Equation (3-31) has been evaluated in Table 3-11 and Figure 3-15 for the typical values of $\omega_0 \approx 1$, $\theta = 0.66$ rad (37°), and fixing $T = \tau_{opt}/\sigma_c = 25\,\tau_{opt}$ suitable for a strato-cumulus cloud. (Also shown for comparison is the result estimated in Reference 2.)

These values probably overestimate the pulse widths at the lower values of τ_{opt}, but we shall adopt them until a verified model for all values of τ_{opt} is developed.

We use the values from Table 3-11 for τ_{opt} = 20, 40, and 60 along with the normalized pulse shape $[\overline{I}(t) = (t_M^{-2})\, t \exp - (t/t_M)]$ to plot representative pulses in Figure 3-16. The drastic dependence of the pulse height and width on optical thickness for the assumed model is clearly seen.

Table 3-11. Typical "Thick" Cloud Pulse Broadening for $\omega_0=1$, $\theta=37°$ and $\sigma_c=0.04\ m^{-1}$

τ_{opt}, Optical Thickness	T, Geometrical Thickness (km)	Δt_c, Pulse Width (μsec)
10	0.25	1.15
20	0.5	3.65
30	0.75	7.08
40	1.0	11.27
50	1.25	16.13
60	1.5	21.55
70	1.75	27.48
80	2.0	33.93
90	2.25	40.88
100	2.5	48.25

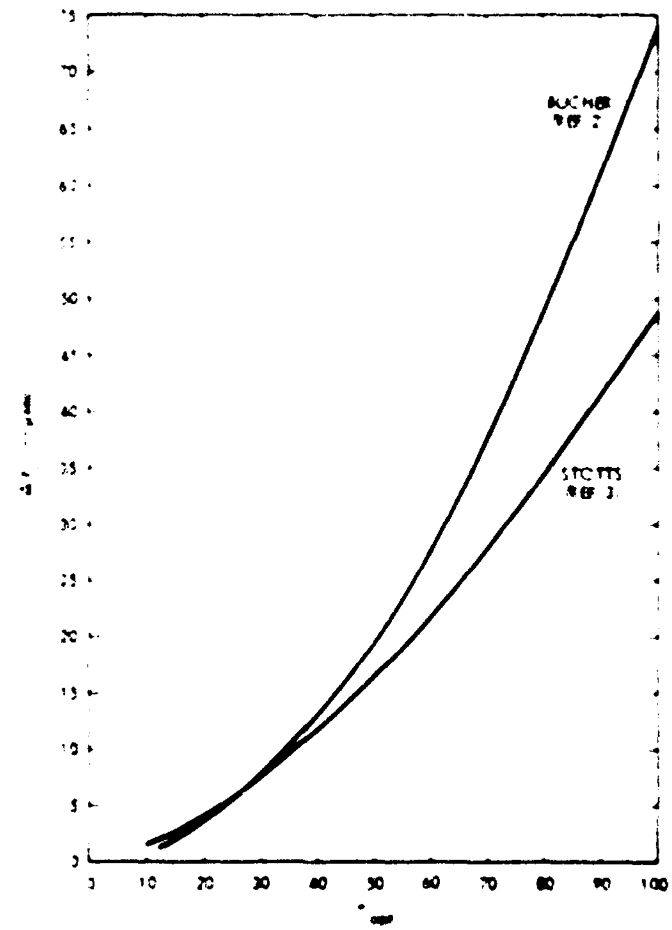


Figure 3-15. Cloud Induced Pulse Stretching as a Function of Optical Thickness ($\sigma_c=0.04\ m^{-1}$, $\omega_0=1$)

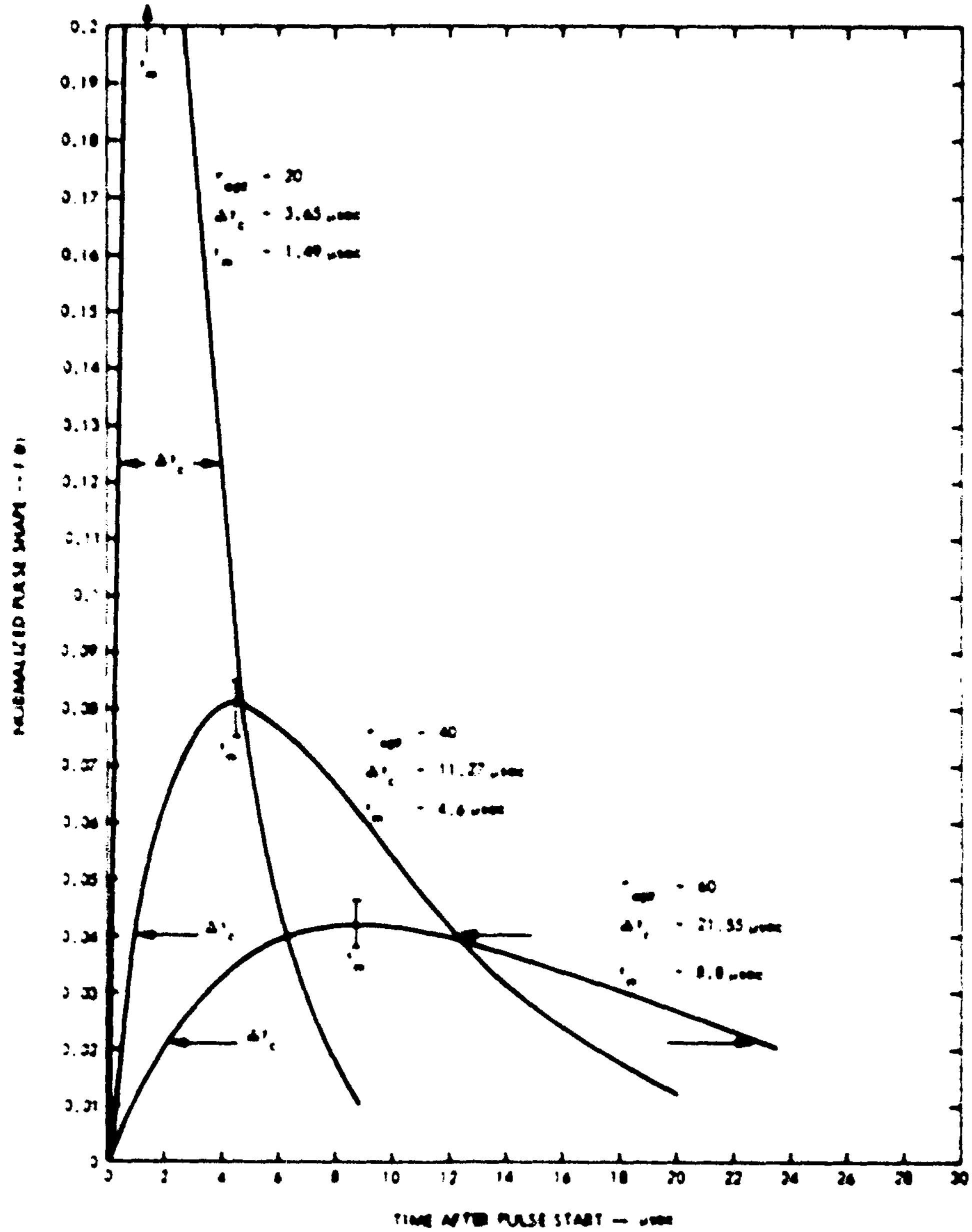


Figure 3-16. Representative Normalized Pulse Shapes as a Function of Cloud Optical Thickness

3.3.9 (Continued)

A careful analysis of the thick cloud to water propagation region has found that it adds a negligible amount relative to Δt_c for reasonable cloud properties and cloud heights. Hence we take

$$\boxed{\Delta t_{cw} = 0, \qquad \tau_{opt} \geq 10 \,. \qquad \text{All zenith angles}} \tag{3-32}$$

We therefore have adopted a complete model for all effects and all optical thicknesses. It shall be used further in the next section.

References for Section 3.3.9

1. All present at the NOSC sponsored Cloud Propagation Symposium, March 1978.
2. E.A. Bucher, "Computer Simulation of Light Pulse Propagation for Communication through Thick Clouds," Applied Optics vol 12 (10) pp 2391-2400, October 1973.
3. L.B. Stotts, "Closed Form Expression for Optical Pulse Broadening in Multiple Scattering Media," Applied Optics vol 17 (4) pp 504-505, Feb 15, 1978.

3.3.10 Overall Signal Equations

The optical detection mechanism responds to the received energy as a function of time, i.e., the instantaneous optical power. The total received optical energy and the instantaneous optical power are related by:

$$E_R = \int_0^{\infty} P_R(t)\, dt \tag{3-33}$$

for

E_R = total received optical energy per pulse, and
$P_R(t)$ = instantaneous received optical power.

Writing

$$P_R(t) = A_E\, f(t), \tag{3-34}$$

for A_E = normalization parameter, and
$f(t)$ = received optical pulse shape,

then

$$A_E = \frac{E_R}{\int_0^{\infty} f(t)\, dt} \tag{3-35}$$

so that

$$P_R(t) = \frac{E_R\, f(t)}{\int_0^{\infty} f(t)\, dt} . \tag{3-36}$$

3.3.10 (Continued)

Using the received pulse shape of Section 3.3.9,

$$f(t) = t \exp -\left(\frac{t}{t_m}\right). \tag{3-37}$$

$$\int_0^\infty f(t)\, dt = t_m^2 \tag{3-38}$$

and

$$\boxed{P_R(t) = E_R\, t \left|\frac{\exp - (t/t_m)}{t_m^2}\right|} \tag{3-39}$$

for $t_m = (2.45)^{-1}$ x (time between half power points). (3-40)

The total received optical energy is given by the range equation:

E_R = (Transmitted Energy per pulse) X (Transmitter optics transmission) X

$$\left(\frac{\text{Area of the receiver}}{\text{Area of the illuminated spot at the receiver depth}}\right) \text{X}$$

(Clear Atmospheric Energy Transmission) X (Cloud Energy transmission) X

(Cloud to Water Energy Transmission) X

(Air-Water Interface Energy Transmission) X (Water Energy Transmission) X

(Receiver Optics Transmission) X

(Fraction of Incident Radiance within Receiver field-of-view). (3-41)

3.3.10 (Continued)

We take

E_p = Transmitted Energy per pulse

η_T = Transmitter Optics Transmission

η_R = Receiver Optics Transmission

d = Diameter of Receiver Aperture

R = Range from source to receiver

$(\pi d^2/4)$ = Area of the receiver

θ_T = Full angle e^{-2} irradiance angle transmitted into*

$R^2 \frac{\pi \theta_T^2}{4}$ = Area of the illuminated spot at the receiver depth.

τ_a = Clear atmosphere energy transmission, as discussed in Section 3.3.1

τ_c = Cloud energy transmission, as discussed in Section 3.3.2

τ_{cw} = Cloud to water energy transmission, as discussed in Section 3.3.3

τ_{aw} = Air-water interface energy transmission, as discussed in Sections 3.3.4 and 3.3.6

τ_w = Water energy transmission, as discussed in Section 3.3.7.

$I(\theta^W)$ = Water radiance distribution, as discussed in Section 3.3.8.

Therefore, the received optical energy is given by

$$E_R = \left(\frac{E_p \, \eta_T}{(\pi \theta_T^2/4)}\right)\left(\frac{(\pi d^2/4)\, \eta_R}{R^2}\right) \tau_a \; \tau_c \; \tau_{cw} \; \tau_{aw} \; \tau_w \; f(\theta_D, \theta_R) \qquad (3\text{-}42)$$

The fraction of the incident radiance within the receiver field-of-view is given by (for perfect alignment between beam axis and receiver axis):

*This assumes such large spots that additional cloud and water spreading is negligible.

3.3.10 (Continued)

$$f(\Omega) = \frac{\int_0^{2\pi} \int_0^{\theta_R} I\,(\theta^w)\; d\,\Omega}{\int_0^{2\pi} \int_0^{\theta_0} I\,(\theta^w)\; d\,\Omega}\,, \quad \theta_R \leq \theta_0 \qquad (3\text{-}43)$$

for

θ_R = half angle of the receiver field-of-view

θ_0 = off-axis angle at which incoming radiance equals zero.

Using the model adopted in Section 3.3.8,

$$f(\Omega) = f(\theta_0, \theta_R) = \frac{1 - \cos\theta_R - \frac{1}{3\sin^2\theta_0}\left[\cos\theta_R \sin^2\theta_R + 2\cos\theta_R - 2\right]}{1 - \cos\theta_0 - \frac{1}{3\sin^2\theta_0}\left[\cos\theta_0 \sin^2\theta_0 + 2\cos\theta_0 - 2\right]} \qquad (3\text{-}43a)$$

$$\text{and} \quad f(\theta_0, \theta_R) = 1, \quad \text{for } \theta_R \geq \theta_0 \,. \qquad (3\text{-}43b)$$

Using Equations (3-42), (3-44) and (3-39) results in the evaluation of the instantaneous optical power in terms of all the other models.

3.4 MODEL UNCERTAINTIES

The sub-models contained in Section 3.3 have a number of uncertainties, due to the lack of available experimental data.

3.4.1 Energy Transmission

The clear atmosphere transmission is well understood at all zenith angles of interest, so the model in Section 3.3.1 has negligible uncertainty.

The cloud energy transmission is not well understood. Areas of uncertainty, not directly treated in the present one-month planned experiment*, include the transition value from thick to thin clouds, the incident zenith angle dependence, the very-thick cloud (optical thickness >50) behavior, and the impact of the single scatter albedo being less than 0.9999. Therefore, future work may modify the model in Section 3.3.2.

The cloud-to-water energy transmission is a small effect and the model in Section 3.3.3 should stand.

The air water interface transmission model in Section 3.3.4 and 3.3.6 has little experimental verification, and may require modification in the high wind speed/large zenith angle regime.

The water energy transmission is not well understood. There are uncertainties with regard to the correct characterization of water loss (absorption with a large fraction of scattering), to thick cloud effects (is there extra water loss here if the water loss coefficient is given by the diffuse attenuation coefficient?). Experimental results support the difference (up to 7 dB) between thick and thin cloud received energy over a particular field-of-view for one type of water at less than operational depths, but no absolute results exist. This area of uncertainty needs to be resolved for the depths of interest and different water types. Therefore, the model in Section 3.3.7 may be modified in the future.

3.4.2 Angular Effects

The SPDPM model in Section 3.3.5 and 3.3.8 is uncertain in two key areas: the shape of the received radiance distribution (including its zenith angle dependency which may be a small effect), and the angular extent of this radiance in clear and cloudy conditions. The present model is based on experimental results at shallow

* To be performed in August/September, 1979.

3.4.2 (Continued)

depths, with one type of water and for small beams incident on the water (clear weather), or the sun (thin to medium cloudy weather). This model assumes that the in-water, air-water interface, and incident angular distributions add in a root sum of squares fashion, which is highly suspect when comparable values arise from more than one contributor, e.g., the thick cloud contribution (modelled as diffuse light hitting the water) and the in-water scattering.

This uncertainty has a large effect on SNR and hardware (the field-of-view requirements interact strongly with the filter size and optical bandpass) and needs to be resolved for the depths of interest, different water types and clear through cloudy weather.

3.4.3 Temporal Effects

The model in Section 3.3.9 for pulse shape and pulse width in the SPDPM is uncertain for both thin and thick cloud conditions, and needs to be experimentally verified.

Consider the zenith angle/field-of-view dependence of the received pulse width in clear weather/thin cloud condition. It may be that pulses more than a few attenuation lengths in duration are unlikely, or that far longer pulses may arise in clearer water conditions. (A related issue is the manner in which the varied temporal effects add up.) This implies a large spread in values, for the pulsewidth, resulting in large signal-to-noise ratio effects (up to $\sqrt{10}$, at least), and needs to be resolved for a receiver at operational depths and in varied water types.

A further uncertainty involves an interaction among energy transmission, field-of-view and time-of-arrival. Does the energy arriving from the "edge" of the field arrive late enough to be useless in signal demodulation? This should also be experimentally ascertained, since no time-resolved underwater experimental results (i.e., for short-pulse sources) presently exist.

(We do not consider here a filter which causes additional pulse distortion. If such a filter does become the leading candidate for OSCAR implementation, the model for both thin and thick clouds would have to be changed.)

Table 3-12 summarizes the uncertainty status of the signal portion of the SPDPM.

Table 3-12. Status of Signal Portion Models of SPDPM

	THIN CLOUD	THICK CLOUD	COMMENTS ON EXPERIMENTAL WORK REQUIRED
<u>ENERGY TRANSMISSION</u>			
Clear Atmosphere	OK	Not applicable	None
Cloud	Unknown, but small effect	Unknown	First experiment planned. Extrapolation TBD.
Cloud to Water	Not applicable	OK	None
Air-Water Interface	OK, at small zenith θ's	OK	Minor
Water	Unknown	Unknown	Needed
<u>ANGULAR EFFECTS</u>			
Shape	Partially verified	Partially verified	Should be done
Out-of-Water Contribution	OK	Partially verified	Should be done if other related work is planned.
In-Water Contribution	Partially verified	Partially verified	Needed for depth and water type.
Combination of Effects	Partially verified	Unknown	Needed
<u>TEMPORAL EFFECTS</u>			
Shape	Unknown	Unknown	Needed
Cloud	Not applicable	Unknown	Needed
Cloud to Water	Unknown	Not applicable	Needed
Water	Unknown	OK (small effect)	Needed
Combination of Effects	Unknown	OK (cloud dominates)	Needed

3.5 "PARAMETER VALUE" UNCERTAINTIES

There are two level of parameter uncertainties: the details of the input parameters to the SPDPM submodels, and the overall data base developments. This section only considers the details of the input parameters; the overall data bases are discussed in Section 5.6 and 6.6*.

3.5.1 Cloud

There are numerous uncertainties in SPDPM inputs.

The inputs to the SPDPM include:

$\langle \cos\theta \rangle$ = mean value of cosine of the single scattering angle. NOSC has set it = 0.875 in their data base, but it is an inferred, not a measured, result. It is uncertain, but has a small impact.

θ = rms angle for single scattering within the cloud. NOSC has set this = 0.64 radian. Again it is an inferred and not measured result, but appears to have little impact.

ω_0 (Single scattering albedo) = 0.9999, but 0.999 or even 0.99 may be more appropriate for some clouds. The impact of the smaller value, for very thick clouds, is less pulse stretching and less energy transmission.

σ_c = average extinction coefficient of the cloud. This depends both on ω_0 and the particle density (as a function of particle size) in the cloud, n(r). ω_0 is not completely known as discussed above, while n(r) is measured by instruments which may have errors from 20% to 100%. Therefore, σ_c for a given cloud type must be considered as uncertain.

T = geometric thickness of the cloud (note, optical thickness = $\sigma_c T$). This is uncertain for a given cloud type (all stratus clouds do not have the same thickness, of course) and poorly defined if the cloud surface is non-uniform. In addition, according to the SPDPM model, it has a greater impact on pulse stretching than does σ_c.

* Moreover only the uncertainties of the environmental parameter are considered here. The system design parameters are described in Section 5.6.

3.5.2 Air Water Interface

There are uncertainties in the values of wind speed to use, and this may have significant impact in bad conditions. For winds less than 20 kts, any uncertainty in the value has a negligible impact.

3.5.3 Water

There are many uncertainties in the water parameters. The inputs to the SPDPM include:

k_i = diffuse attenuation coefficient of the i'th water layer. The values presented by NOSC are uncertain in absolute magnitude, but the wavelength trend is correct.

D_i = thickness of the i'th water layer. It is uncertain and has a significant impact on the system if the upper dirty water layer is thin compared to the operational depth.

S_i' = RMS angle for a single scattering event in the water. The value provided by NOSC is uncertain since it is based on an empirical fit to data at shallow depths and for one type of water. This uncertainty could have a large impact on the required clear weather receiver field of view.

S = Scattering coefficient for the entire path. It is uncertain whether its value should be taken independent of depth, and in its absolute value for all water types.

n - water index of refraction. No uncertainty.

Table 3-13 summarizes the uncertainty status of all the parameters for the signal portion of the SPDPM.

Table 3-13. Status of "Input Parameters" to the Signal Portion of the SPDPM

PARAMETER	STATUS	COMMENTS ON EXPERIMENTAL WORK REQUIRED
Clear Atmosphere	OK	None
Cloud:		
$\langle \cos$ [illegible]$\rangle$	OK	None
[illegible]	OK	None
[illegible]$_o$	Partially known	No direct experiment possible
[illegible]$_c$	Partially known	Some work is planned during first cloud experiment. Equipment may be too innacurate for good results
T	Partailly known	Interpretation of data required
Cloud-to-Water	OK	None
Air Water Interface	Ok, for low wind speed	Some required for bad conditions.
Water:		
k_1	Partially known	Required if not done by other contractors
[illegible]$_1$	Partially known	Required if available data not able to be interpreted.
[illegible]$_{s1}$	Partially known	Required as a function of depth and water type.
S	Partially known	May become available for surface water from ongoing work. Needed for water at depth.
n	OK	None

GTE SYLVANIA

Section 4

SINGLE PULSE DOWNLINK PROPAGATION MODEL - NOISE

This section discusses the model for the propagation of the noise relative to a single signal pulse. The section is organized as follows:

4.1 Model Philosophy and Flow Chart-Noise

This section considers the basic approach used in the detailed models presented in Section 4.3, and presents flow charts showing the inter-relationship of the sub-models and their required inputs. (These inputs are discussed in more detail in Section 4.2).

4.1.1 Philosophy of Approach - Noise

Since all the background sources that must propagate through clouds are continuous in time, that part of the modeling related to the temporal effects is not present here. This simplifies the noise modeling.

On the other hand, the sources of the noise are so different (sun, moon, skylight, star-light, bioluminescence, shot noise in the receiver amplifier, detector dark current, etc.), that it has been difficult to develop a single unified approach to all of them. The approach, therefore, is to:

(1) Express the noise contribution as a noise-equivalent-optical-power, (NEP_{TOT}) which is the root sum of squares of all the noise-equivalent-optical power contributions of the individual noise components. The NEP_{TOT} is then directly comparable to the instantaneous received optical power $P_R(t)$ developed in Section 3, and the signal-to-noise ratio is $\hat{P}_R/NEP_{TOT}$; for $\hat{P}_R$ the peak value of the received signal power;

(2) Take the out-of-water background sources in terms of equivalent exo-atmospheric radiances, and then their propagation through the atmosphere and water path is treated in parallel with the signal energy transmission of Section 3.3. The angular effects and noise radiance distribution are also treated in a manner similar to that of the signal in Section 3;

(3) Take the noise contributions of the background sources as the 1-sigma point in the fluctuations generated in the signal current by their steady presence, and express their contributions in terms of an equivalent optical power;

(4) Treat the amplifier shot noise, detector dark current and signal shot noise in the standard way, and express their contributions in terms of an equivalent optical power;

4.1.1 (Continued)

(5) Present the modeling in a modular fashion, so that the effect of each portion of the path is evident. In addition, as further experiments and analyses are undertaken, pieces of the model may be upgraded without requiring extensive modifications to the total model;

(6) Separate the cloud conditions into clear/thin cloud corresponding to an optical thickness (τ_{OPT})<10, and thick cloud for τ_{OPT}>10. Below τ_{OPT}=10 one set of sub-models is assumed to apply, while above it a different set applies. In many cases these sub-models do not correspond at τ_{OPT}=10, and so the overall model should only be used for τ_{OPT}<10 and τ_{OPT}>>10. (Further analysis and experiments on the "multiple forward scattering" region should enable the sub-models to be upgraded, and this inconsistency removed).

(7) Assume appropriate and simple analytic forms for at-present unknown functions such as the radiance distributions. This enables us to present analytic results (except for the receiver axis offset from the beam axis of the incident radiation), which is an aid to a physical understanding of the situation.

4.1.2 Model Flow Chart-Noise

A schematic of the overall downlink single pulse noise equivalent power propagation model is shown in Figure 4-1. Given the input parameters, the path energy transmission and angular and radiance distributions are derived for the four "exo-atmospheric" background sources. Then, using additional input data, the average background power for all background sources is derived, and the noise-equivalent optical power for all the noise components.

Figure 4-2 is a detailed flow diagram of the direct sunlight contribution, showing the calculations that must occur to arrive at the required output. (The flow charts for the moonlight, blue sky-light and starlight/zodiacal light are identical to this one, while the simpler one for the bioluminscence is shown in Figure 4-3):

(I) The input parameters are listed in the eight ellipses on the left hand side of the figure, including source, clear atmosphere, cloud, cloud to water, air/water interface, water, receiver and signal characteristic parameters. (The symbols are defined in the glossary in Section 2, and also in the input discussion in Section 4.2):

(II) The calculation equations are represented by the rectangular boxes. Within each box is the symbol for the parameter to be calculated and the equation number (from Section 4.3) for the equation to be used to calculate that parameter.

The first quantity calculated is the cloud optical thickness, τ_{OPT}, since this determines which equation should be used to calculate many other parameters. Whenever // appears in a rectangular box, the equation number preceeding it refers to $\tau_{OPT} \geq 10$, while the equation number following it refers to $\tau_{OPT} < 10$. Hence, given the value of τ_{OPT}, the rest of the models to be used are specifically determined.

(III) The second set of calculations performed are of two types:

(a) Path transmission, including τ_a', τ_c', τ_{cw}', τ_{aw}', and τ_w';

(b) Angular and radiance distribution including f_a, f_{aw}, f_w, ϕ_0 and $f'(\theta_R, \phi_0, t)$;

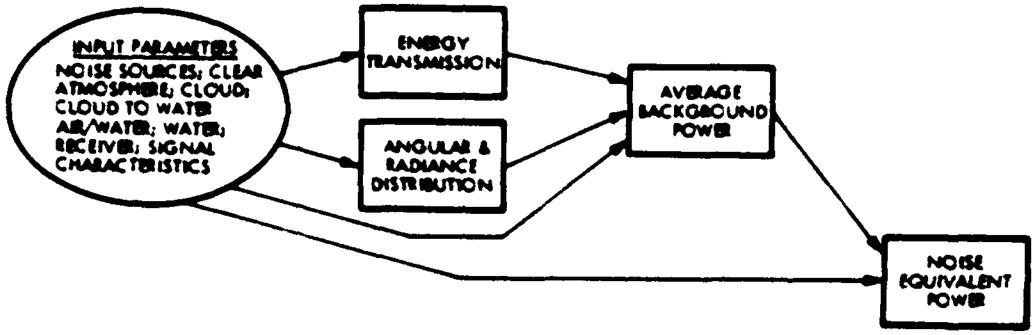


Figure 4-1. Schematic of Typical Single-Pulse Noise Equivalent Power Downlink Propagation Model

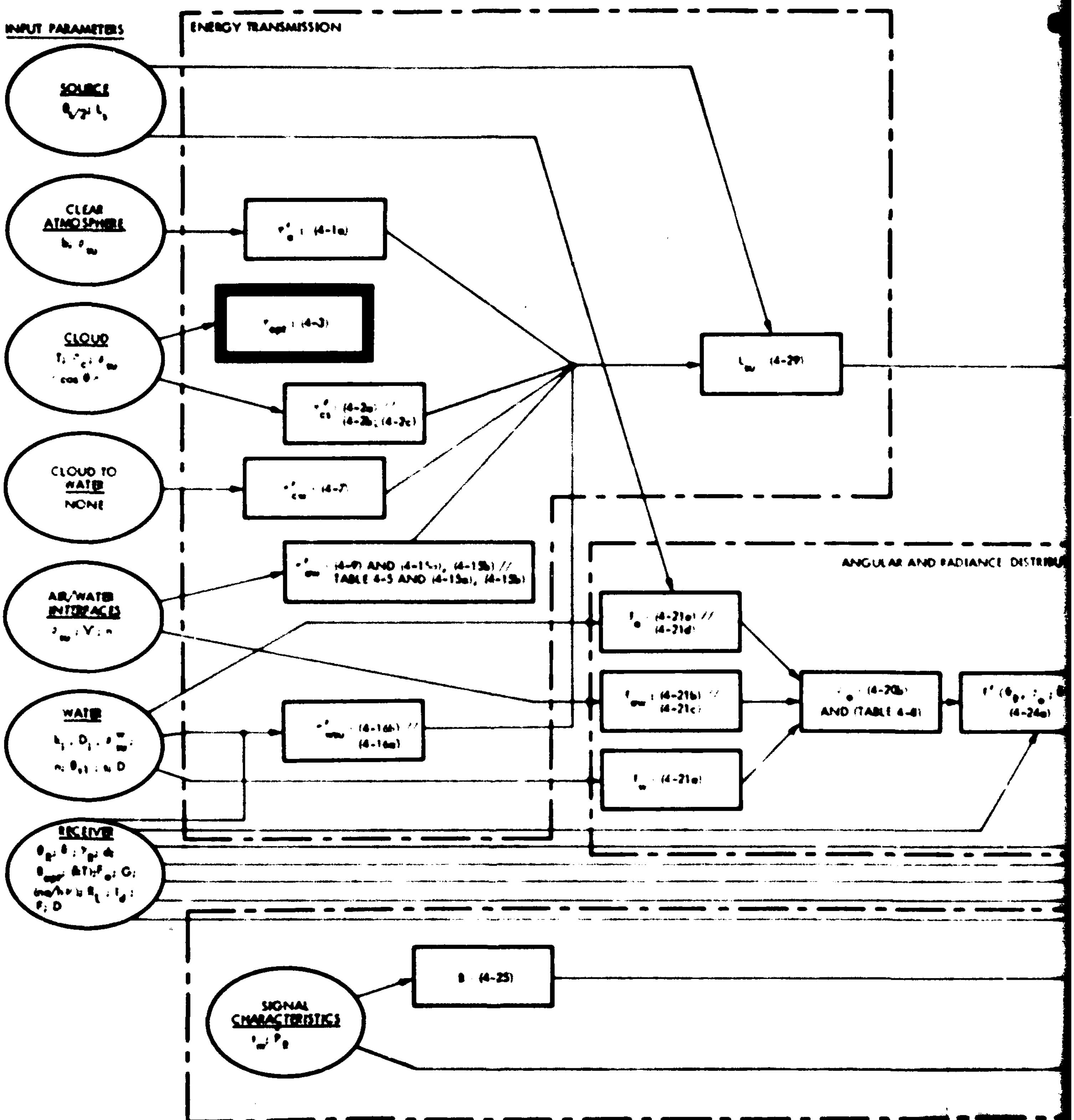
4.1.2 (Continued)

(IV) The path transmission, angular and radiance distribution, source and receiver parameters are then used to calculate the average background power due to that source.

(V) The total average background power due to all sources is then calculated;

(VI) The total average background power, receiver and signal characteristics are then used to calculate the total noise equivalent optical power.

Figure 4-3 shows the flow chart for calculating the average background power due to bioluminescence, P_{BL}. This value of P_{BL} enter into Figure 4-2 in the $\sum_i P_B^i$ calculations.


INPUT PARAMETERS
ENERGY TRANSMISSION
SOURCE
CLEAR ATMOSPHERE
CLOUD
CLOUD TO WATER
NONE
AIR/WATER INTERFACES
WATER
RECEIVER
SIGNAL CHARACTERISTICS
(4-1a)
(4-3)
(4-2a)
(4-2b); (4-2c)
(4-29)
(4-9) AND (4-15a), (4-15b) //
TABLE 4-5 AND (4-15a), (4-15b)
(4-16b) //
(4-16a)
(4-21a) //
(4-21d)
(4-21b) //
(4-21c)
(4-21e)
(4-20b)
AND (TABLE 4-4)
(4-24a)
(4-25)

1

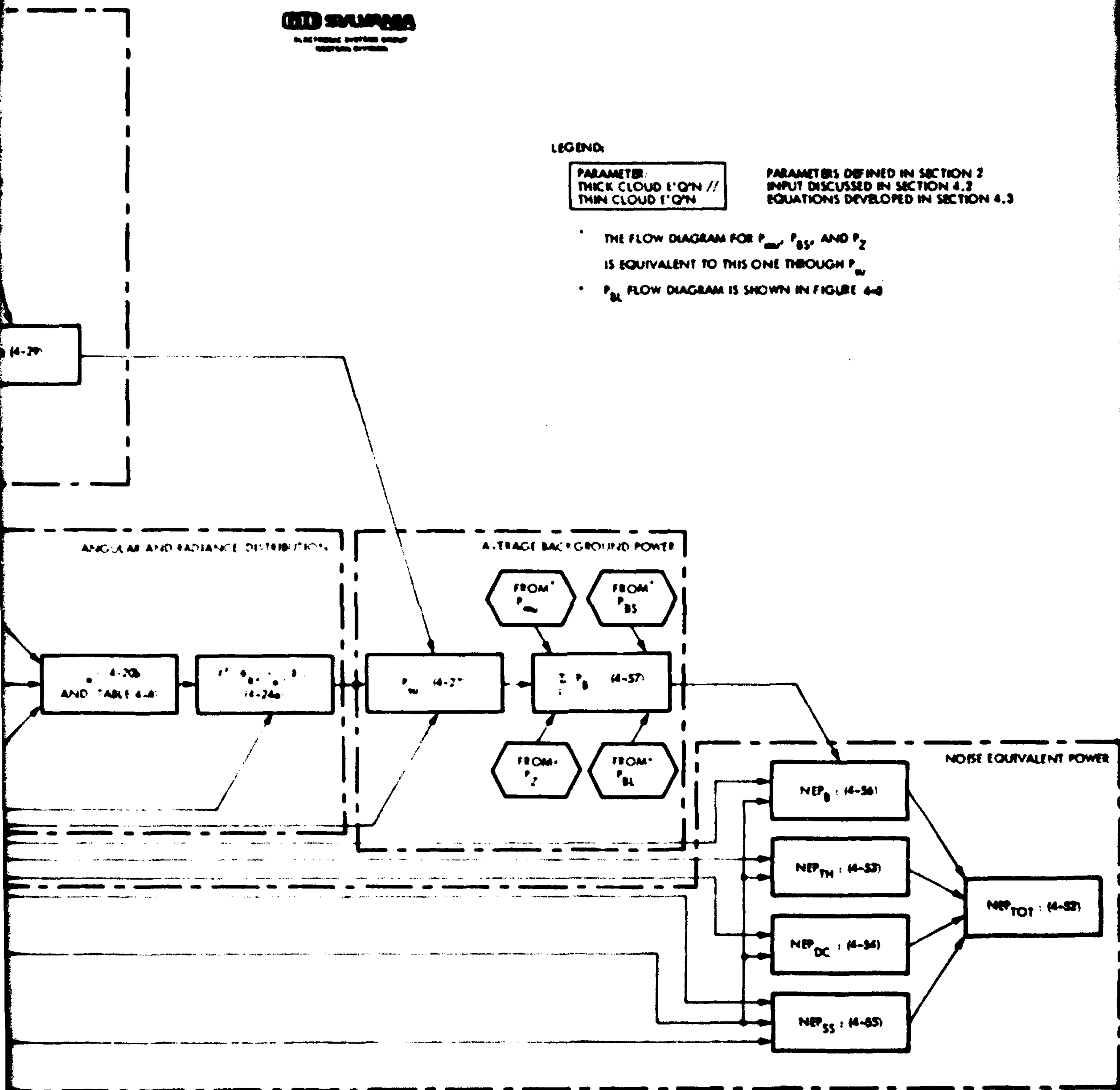


Figure 4-2. Flow Diagram of Single-Pulse Downlink Propagation Model (Noise)

1 2

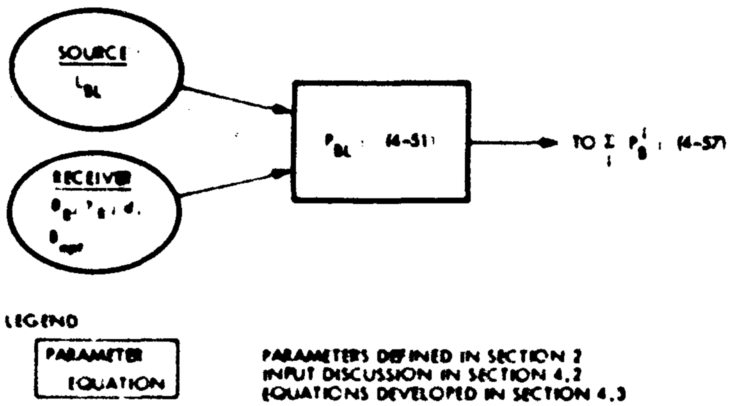


Figure 4-3. Flow Diagram of Single-Pulse Downlink Propagation Model Noise due to Bioluminescence

4.2 Input Information for Noise Calculation

This section discusses the form (and values in some cases) of the required inputs to the noise model, in terms of the eight categories: source, clear atmosphere, cloud, cloud to water, air/water interface, water, receiver and signal characteristics.

4.2.1 Source

There are five sources of the average background, which are treated here as independent. These sources are: sunlight; moonlight; blue sky-light; starlight/zodiacal light; and bioluminescence.

It is expected that these sources will be treated rationally when using them as inputs, so that when sunlight is present, only the blue-skylight will be expected with a non-zero value; and when moonlight is considered to be non-zero, only the starlight/zodiacal light and bioluminescence will be used with non-zero values.

We consider each of the five sources separately.

Sun

Symbol	Description	Units
$\theta_{s/2}$	The half-angle subtended by the sun at the earth. Its value is taken as[1] $4.65\ 10^{-3}$ radians.	Radians
L_s	Effective exo-atmospheric spectral radiance of the sun. This is the result of taking the exo-atmospheric irradiance of the sun and treating it as a hemispheral source. The result is[2] $(2000/\pi) = 635.62$ watts/(meters)^2 (steradians)(micron) over the blue-green region.	Watts/(meters)^2 (steradians)x(microns)

4.2.1 (Continued)

Moon

Symbol	Description	Units
$\theta_{m/2}$	The half-angle subtended by the moon at the earth. Its value is equal to[3] $\theta_{s/2}$ = 4.65 (10^{-3}) radians.	Radians
L_m	Effective exo-atmospheric spectral radiance of the moon. As for the sun, this is the result of taking the exo-atmospheric irradiance of the moon and taking it as a hemispherical source. The result is[4] $(4.3/\pi)(10^{-3})$ = 1.37 (10^{-3}) watts/(meters)^2 (Steradians) (microns) for a full moon in the blue-green region.	$\frac{\text{Watts}}{(\text{Meters})^2(\text{Steradians})(\text{Microns})}$

Blue Skylight

Symbol	Description	Units
L_B	Effective exo-atmospheric spectral radiance of the blue-sky light. This is estimated from a private communication (from L. Stotts of NOSC) to be 100 watts/ $\left[(\text{meter})^2 (\text{srad}) (\text{micron})\right]$.	$\frac{\text{Watts}}{(\text{Meters})^2(\text{Steradians})(\text{Microns})}$

4.2.1 (Continued)

Starlight/Zodiacal Light

Symbol	Description	Units
L_Z	Effective exo-atmospheric spectral radiance due to all non-lunar night time sources. The value[6] is 3 (10^{-6}) [watts/(meters)^2(srad)(micron)] in the blue-green spectral region.	[Watts/(meters)^2 (Steradians)(microns)]

Bioluminescence

Symbol	Description	Units
L_{BL}	Spectral irradiance of the ambient bioluminesce sources at the aperture of the submarine receiver. The value for this parameter is least well known of all the background contributors. We use the values provided in the SAOCS RFP, so that[7] $L_{BL} = (10^{-3})$ watts/m^2 microns.	[Watts/(meters)^2 (microns)]

4.2.2 Clear Atmosphere

The required parameters are:

Symbol	Description	Units
b	Effective clear atmospheric optical thickness. For a zenith transmission of 70%; b = 0.357	
θ_{su}	In-air solar zenith angle	Radians
θ_{mu}	In-air lunar zenith angle	Radians

4.2.3 Cloud

The required parameters are:

Symbol	Description	Units
T	Geometric or physical thickness of the cloud.	Meters
σ_c	Average extinction coefficient of the cloud.	$(\text{Meters})^{-1}$
θ_{su}	In-air solar zenith angle	Radians
θ_{mu}	In-air lunar zenith angle	Radians
$<\cos\theta>$	The average value of the cosine of the scattering angle for single scattering within the cloud.	
ω_0	Single scattering albedo of a cloud particle	

4.2.4 Cloud to Water

No parameters in this area affect the noise properties.

4.2.5 Water

The required parameters are:

Symbol	Description	Units
k_i	Diffuse attenuation coefficient of the i'th water layer.	$(\text{Meters})^{-1}$
D_i	Thickness of the i'th water layer	(Meters)
θ^w_{su}	In-water Solar Zenith Angle	Radians
θ^w_{mu}	In-water Lunar Zenith Angle	Radians
n	Water Index of refraction	
θ_{sl}	Root-Mean-Square angle for a single scattering event in the water.	Radians
s	Scattering coefficient for the entire water path	$(\text{Meters})^{-1}$
D	Depth of the submarine receiver	Meters

4.2.6 Air/Water Interface

The required parameters are:

Symbol	Description	Units
θ_{su}	In-air solar zenith angle	Radians
θ_{mu}	In-air lunar zenith angle	Radians
V	Surface Wind Speed	Meters/Second
n	Water Index of Refraction	

4.2.7 Receiver

The required parameters are:

Symbol	Description	Units
θ_R	Half-angle of the receiver field of view	Radians
[illegible]	Off-set angle between the in-water noise source beam and the receiver optical axis	Radians
τ_R	Transmission of the receiver optical chain	
d	Diameter of the receiver optical aperture	Meters
B_{opt}	Passband of the optical filter	Microns
(kT)	Thermal Noise contribution in the amplifier	Joules
F_a	Excess amplifier noise over thermal noise	
G	Gain of the photo-detector	
$(\eta e/h\nu)$	Responsivity of the photo-surface	Amps/Watts
R_L	Load Resistance following the photo-detector	Ohms
I_d	Dark current at the detector cathode	Amps
F	Excess noise in the photo-detector gain	
D	Depth of the submarine receiver	Meters

4.2.8 Signal Characteristics

Two parameters from the signal characteristics which enter into the Noise calculations are:

Symbol	Description	Unit
t_M	Time after pulse initiation at which it peaks, for a $t \exp - (t/t_M)$ shape.	Seconds
$\hat{P}_R$	Peak value of the received optical signal power.	Watts

References for Section 4.2

1. Handbook of Geophysics, Revised Edition (The MacMillan Co., New York, 1960) pp 17-1, 17-2.

2. Reference 1, p 16-15, Figure 16-10.

3. R.C. Haynes, Introduction to Space Science, John Wiley and Sons, (New York, 1971) pp 4-5.

4. W.K. Pratt, Laser Communication Systems, John Wiley and Sons (New York, 1969) p. 123, Figure 6-9.

5. Reference 4, p 121, Figure 6-6.

6. Reference 4, p 122, Figure 6-7.

7. T. Flom, P.J. Titterton, et al, "Optical Submarine Communication by Aerospace Relay (OSCAR)," Secret Report, Interim Report No. 2, May 1, 1978, Contract No. N00039-77-C-0100, p 3-22 to 3-24.

4.3 SUB-MODELS

This section develops all the equations used in the calculation of the noise contribution to the total noise equivalent optical power.

Sections 4.3.1, 4.3.2, 4.3.3, 4.3.4, 4.3.6, and 4.3.7 consider the path transmission of the energy.

Sections 4.3.5 and 4.3.8 consider the angular effects and the distribution of the received radiance.

Section 4.3.9 considers the electrical detection bandwidth in terms of the received pulse width.

In each of these sections, after the equations are developed they are evaluated for typical cases in both tables and figures.

Sections 4.3.10 through 4.3.14 then derive the average background optical power for the five types of background sources, and Section 4.3.15 presents the expression for the total noise equivalent optical power due to all noise sources.

4.3.1 Clear Atmospheric Transmission-Noise

In the absence of any clouds or aerosols, the clear atmospheric transmission is described by the term τ_a'. Using the approximate AFCRL model[1], the solar (or lunar) zenith angle dependence is given by:

$$\boxed{\tau_a' = \exp\left(-b \sec \phi_{su}\right),} \tag{4-1a,b}$$

for τ_a' = solar (or lunar) clear atmospheric transmission

b = effective clear atmosphere optical thickness

ϕ_{su} = solar zenith angle.

(For the lunar case, ϕ_{su} is replaced by ϕ_{mu} = lunar zenith angle.)

The typical value of b is determined by

$$\tau_a' (\phi_{su} = 0) = 0.7 = \exp(-b),$$

or $b = 0.357$.

Table 4-1 and Figure 4-4 show the values of τ_a' as a function of solar zenith angle.

The other two out-of-water sources of background radiation are taken as uniformly distributed over the hemisphere. Then the effective atmospheric transmission is weighted by the transmission at each zenith angle, or, for the blue-sky and the stellar sources,

$$\tau_a' = \frac{\int_0^{2\pi} d\phi \int_0^{\pi/2} \sin\theta \, d\theta \exp - [b \sec \theta]}{\int_0^{2\pi} d\phi \int_0^{\pi/2} \sin\theta \, d\theta}$$

$$\boxed{\tau_a' = E_2(b) \quad \text{for blue sky or stellar background,}} \tag{4-1c, d}$$

Table 4-1. Typical Clear Atmospheric Transmission (b=0.357)

θ_{su}, Solar Zenith Angle	τ_a', Clear Atmospheric Transmission
0	0.7
10	0.7
20	0.68
30	0.66
40	0.63
50	0.57
60	0.49
70	0.35
80	0.13

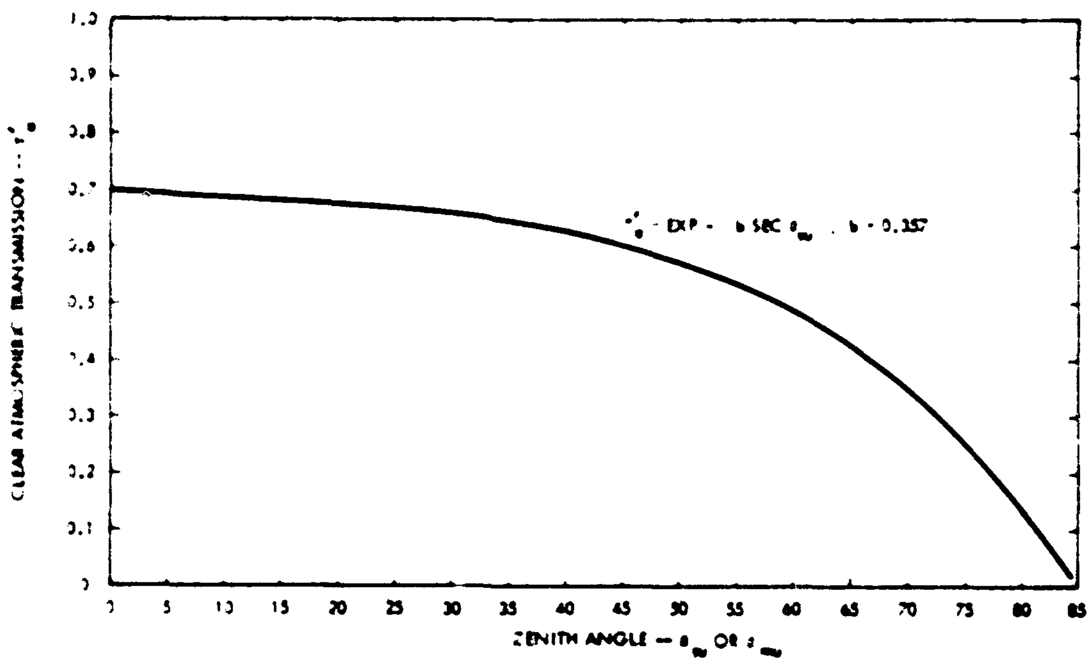


Figure 4-4. Typical Clear Atmospheric Transmission (b = 0.357)

with $E_2(b)$ = exponential integral[2].

For b = 0.357, E_2 (0.357) = 0.42.

<u>References for Section 4.3.1</u>

1. R. A. McClatchey, R. W. Fenn, J. E. A. Selby, F. E. Volz and J. S. Garing "Optical Properties of the Atmosphere (Revised)" AFCRL-71-0279, 10 May 1971.

2. M. Abramowitz and I. A. Stegun, editor, <u>Handbook of Mathematical Functions</u>, NBS Applied Mathematics Series 35, Government Printing Office, November 1970. p 228.

4.3.2 Cloud Energy Transmission - Noise

The transmission of sunlight or moonlight by clouds does not have an experimentally verified expression. Most work in cloud transmission has been a broadband treatment of transmitted irradiance (watts/m^2), and there have been no experiments which collected the total energy emerging from thick or thin clouds.

We propose to adopt a number of different (but consistent) models, depending on the characteristics of the noise source.

For the sun and moon we shall adopt the same model as for the signal (Section 3.3.2) with the exception that both the sunlight and moonlight do spread out with zenith angle, and thus the extra cosine factor is always present.

Therefore, for the sun

$$\tau'_{cs} = \left\{\frac{1}{\tau_{opt}\,(1 - \langle\cos\theta\rangle) + 1.42}\right\}\left\{\cos\theta_{su}\right\}\left\{1.69 - 0.5513\,\theta_{su} + 2.7173\,\theta_{su}^2 - 6.9866\,\theta_{su}^3 + 7.1446\,\theta_{su}^4 - 3.4249\,\theta_{su}^5 + 0.6155\,\theta_{su}^6\right\} \times \left\{2\sqrt{3(1-\langle\cos\theta\rangle)(1-\omega_o)}\right\}\left\{\tau_{OPT} + \frac{1.42}{1-\langle\cos\theta\rangle}\right\}$$

$$\times \left\{\frac{\exp -\left[\sqrt{3(1-\langle\cos\theta\rangle)(1-\omega_o)}\left\{\tau_{OPT} + \frac{1.42}{1-\langle\cos\theta\rangle}\right\}\right]}{1 - \exp -\left[2\sqrt{3(1-\langle\cos\theta\rangle)(1-\omega_o)}\left\{\tau_{OPT} + \frac{1.42}{1-\langle\cos\theta\rangle}\right\}\right]}\right\}$$

for $\tau_{opt} \geq 10$; (4-2a)

$$\tau'_{cs} = \left\{1 - 0.085\,\tau_{opt}\left[\frac{1.69}{10(1-\langle\cos\theta\rangle) + 1.42}\right]\right\}\left[\cos\theta_{su}\right]^2,$$

for $\tau_{opt} \leq 10$; (4-2b)

$$\tau'_{cs} = \cos\theta_{su},$$

for $\tau_{opt} = 0$. (4-2c)

4.3.2 (Continued)

where

τ'_{cs} = cloud energy transmission of direct sunlight,

τ_{opt} = optical thickness of the cloud

$\langle\cos\theta\rangle$ = mean cosine of the scattering angle

and

ϕ_{su} = solar zenith angle

As before,

$$\tau_{opt} = T\,\sigma_c \tag{4-3}$$

for T = geometrical thickness of the cloud, and σ_c = mean extinction of the cloud.

For the moon

$$\tau'_{cm} = \left\{\frac{1}{\tau_{opt}\,(1-\langle\cos\theta\rangle) + 1.42}\right\}\left\{\cos\phi_{mu}\right\}\Big\{1.69 - 0.5513\,\phi_{mu} + 2.7173\,\phi_{mu}^2$$

$$- 6.9866\,\phi_{mu}^3 + 7.1446\,\phi_{mu}^4 - 3.4249\,\phi_{mu}^5 + 0.6155\,\phi_{mu}^6\Big\}$$

$$\times \left\{2\sqrt{3\,(1-\langle\cos\theta\rangle)\,(1-\omega_o)}\right\}\left\{\tau_{OPT} + \frac{1.42}{1-\langle\cos\theta\rangle}\right\}$$

$$\times \left\{\frac{\exp - \left[\sqrt{3\,(1-\langle\cos\theta\rangle)(1-\omega_o)}\left\{\tau_{OPT} + \frac{1.42}{1-\langle\cos\theta\rangle}\right\}\right]}{1 - \exp - \left[2\sqrt{3\,(1-\langle\cos\theta\rangle)\,(1-\omega_o)}\left\{\tau_{OPT} + \frac{1.42}{1-\langle\cos\theta\rangle}\right\}\right]}\right\}$$

$$\text{for } \tau_{OPT} \geq 10; \tag{4-4a}$$

and

$$\tau'_{cm} = \left\{1-0.085\,\tau_{opt}\right\}\left\{\left[\frac{1.69}{10\,(1-\langle\cos\theta\rangle) + 1.42}\right]\right\}(\cos\phi_{mu})^2 ,$$

$$\text{for } \tau_{OPT} \leq 10; \tag{4-4b}$$

and

$$\tau_{cm} = \cos\phi_{mu} \qquad \text{for } \tau_{opt} = 0. \tag{4-4c}$$

4.3.2 (Continued)

where

τ_{cm}' = cloud energy transmission of direct moonlight,

and θ_{mu} = lunar zenith angle.

The typical energy transmission (for $\langle \cos \theta \rangle$ = 0.83) described by Equations (4-2) and (4-4) is shown in Table 4-2 and Figure 4-5.

The zenith angle dependence for both regimes of τ_{opt} is shown in Table 4-3 and Figure 4-6.

Again there is a discontinuity in the zenith angle dependence at τ_{opt} = 10 which we shall ignore, pending a verified model of cloud energy transmission.

The other two out-of-water sources of the ambient background are approximated as uniform sources distributed across the full hemisphere. Then an extra factor arises due to their distribution in angle of incidence upon the cloud. This extra factor is given by

$$\int_0^{\pi/2} f(\theta) \sin\theta \, d\theta ,$$

Table 4-2. Typical Energy Transmission for Sunlight and Moonlight at Zenith ($\langle\cos\theta\rangle$ = 0.83, ω_0 = 1.

τ_{opt}, Optical Thickness	τ_{cs}', τ_{cm}', Cloud Energy Transmission
0	1
2	0.91
4	0.82
6	0.72
8	0.63
10	0.54
20	0.35
30	0.26
40	0.21
50	0.17
60	0.15
70	0.13
80	0.11
90	0.10
100	0.09

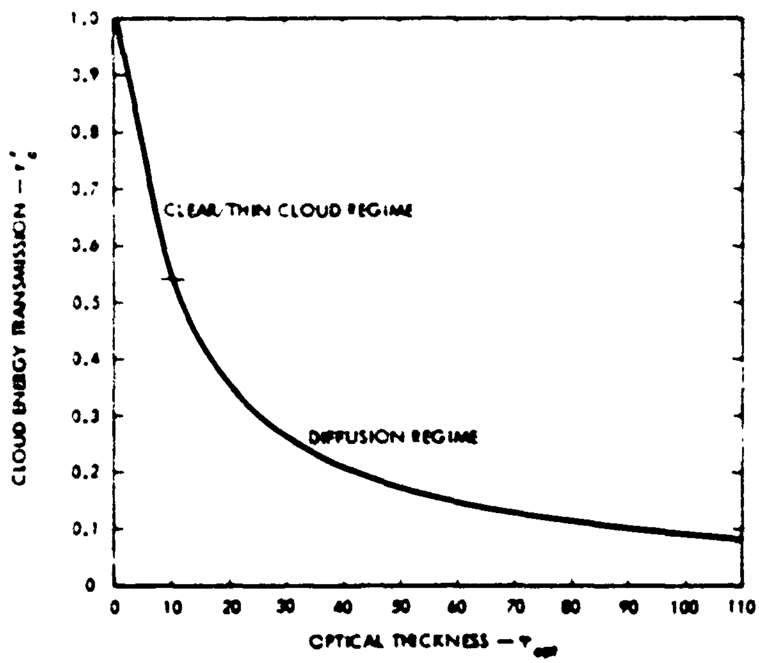


Figure 4-5. Thick and Thin Cloud Energy Transmission Versus Optical Thickness, for $\langle\cos\theta\rangle$ = 0.83, ω_0 = 1.

Table 4-3. Zenith Angle Dependence of Sun and Moon Cloud Energy Transmission (Normalized to $\phi_{su} = 0$ and $\phi_{mu} = 0$)

ϕ_{su}, ϕ_{mu} Zenith Angle	Thick Cloud Dependence ($\tau_{opt} \geq 10$)	Thin Cloud Dependence ($\tau_{opt} \leq 10$)
0	1	1
10	0.96	0.97
20	0.90	0.88
30	0.79	0.75
40	0.66	0.59
50	0.50	0.41
60	0.34	0.25
70	0.20	0.12
80	0.08	0.03
85	0.03	0.008

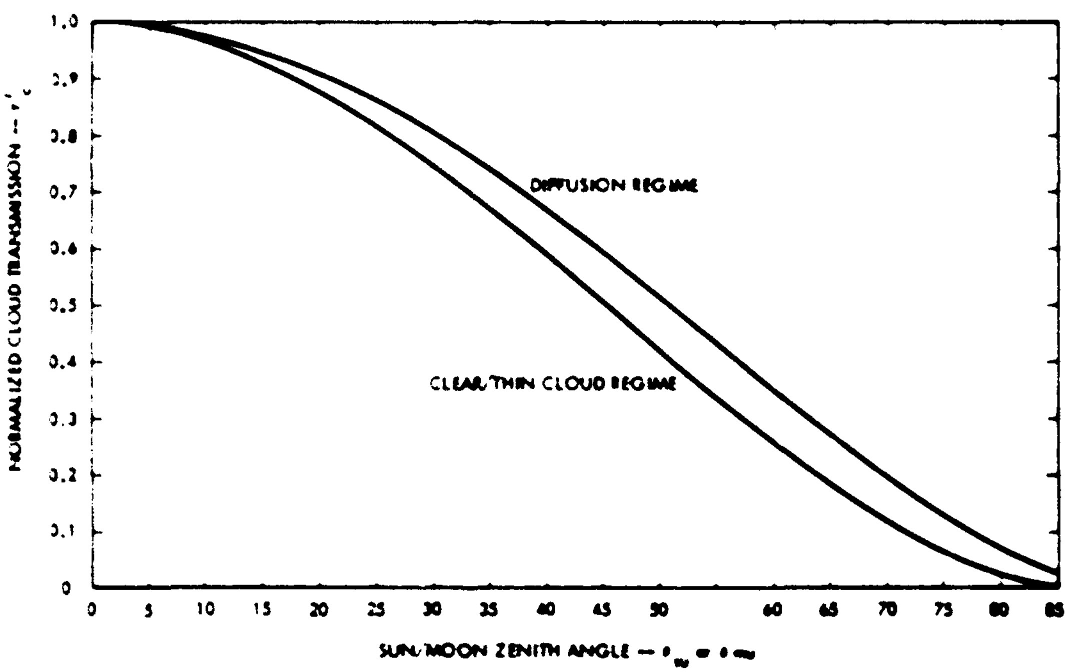


Figure 4-6. Thin and Thick Cloud Zenith Angle Dependence of Cloud Transmission Normalized to Zenith

4.3.2 (Continued)

for $f(\theta) = 1 - 0.3262\,\theta + 1.608\,\theta^2 - 4.1341\,\theta^3 + 4.2276\,\theta^4 - 2.0266\,\theta^5 + 0.3642\,\theta^6$

$= \cos\theta$ for thin clouds

θ = zenith angle of the incident light.

Evaluating this integral we find it equals approximately 2/3 for thick clouds and 1/2 for thin ones.

Therefore, for the blue sky background, the cloud energy transmission is given by

$$\tau'_{CB} = \frac{2}{3}\left\{\frac{1.69}{\tau_{opt}\,(1-\langle\cos\theta\rangle) + 1.42}\right\}\left\{2\sqrt{3(1-\langle\cos\theta\rangle)\,(1-\omega_0)}\right\}\left\{\tau_{opt} + \frac{1.42}{1-\langle\cos\theta\rangle}\right\}$$

$$\times\left\{\frac{\exp -\left[\sqrt{3(1-\langle\cos\theta\rangle)\,(1-\omega_0)}\left\{\tau_{opt} + \frac{1.42}{1-\langle\cos\theta\rangle}\right\}\right]}{1 - \exp -\left[2\sqrt{3(1-\langle\cos\theta\rangle)\,(1-\omega_0)}\left\{\tau_{opt} + \frac{1.42}{1-\langle\cos\theta\rangle}\right\}\right]}\right\}$$

for $\tau_{opt} \geq 10$, (4-5a)

and $$\tau'_{CB} = \frac{1}{2}\left\{1-0.085\,\tau_{opt}\left[\frac{1.69}{10\,(1-\langle\cos\theta\rangle) + 1.42}\right]\right\}$$

for $\tau_{opt} < 10$, (4-5b)

and $\tau'_{CB} = 1$ for $\tau_{opt} = 0$. (4-5c)

4.3.2 (Continued)

The discontinuity at $\tau_{opt} = 10$ is again present, and again neglected until a better experimentally-verified model is derived.

Note Equations (4-5a, b) are independent of solar zenith angle. However, the strength of the radiance incident from the blue sky does depend on solar zenith angle.

For the moonless night case, the stellar/zodiacal light cloud energy transmission is given by

$$\tau'_{CZ} = \frac{2}{3}\left\{\frac{1.69}{\tau_{opt}\,(1-\langle\cos\theta\rangle)+1.42}\right\}\left\{2\sqrt{3(1-\langle\cos\theta\rangle)\,(1-\omega_0)}\right\}\left\{\tau_{opt}+\frac{1.42}{1-\langle\cos\theta\rangle}\right\}$$
$$\times\left\{\frac{\exp-\left[\sqrt{3(1-\langle\cos\theta\rangle)\,(1-\omega_0)}\left\{\tau_{opt}+\frac{1.42}{1-\langle\cos\theta\rangle}\right\}\right]}{1-\exp-\left[2\sqrt{3(1-\langle\cos\theta\rangle)\,(1-\omega_0)}\left\{\tau_{opt}+\frac{1.42}{1-\langle\cos\theta\rangle}\right\}\right]}\right\} \qquad (4\text{-}6a)$$

and

$$\tau'_{CZ} = \frac{1}{2}\left\{1-0.085\,\tau_{opt}\left[\frac{1.69}{10\,(1-\langle\cos\theta\rangle)+1.42}\right]\right\}$$

$$\text{for } \tau_{opt} < 10, \qquad (4\text{-}6b)$$

and

$$\tau'_{CZ} = 1, \qquad \text{for } \tau_{opt} = 0 \qquad (4\text{-}6c)$$

Table 4-4 and Figure 4-7 show a typical cloud energy transmission as a function of cloud optical thickness for these uniform sources of ambient background.

Table 4-4. Typical Cloud Energy Transmission for Blue Skylight and Stellar/Zodiacal Light ($\langle\cos\theta\rangle = 0.83$, $\omega_0 = 1.$)

τ_{opt}, Optical Thickness	τ_{cb}', τ_{cz}' Cloud Energy Transmission
0	1
2	0.46
4	0.41
6	0.36
8	0.32
10	0.27 (thin); 0.36 (thick)
20	0.23
30	0.17
40	0.14
50	0.11
60	0.1
70	0.087
80	0.073
90	0.067
100	0.06

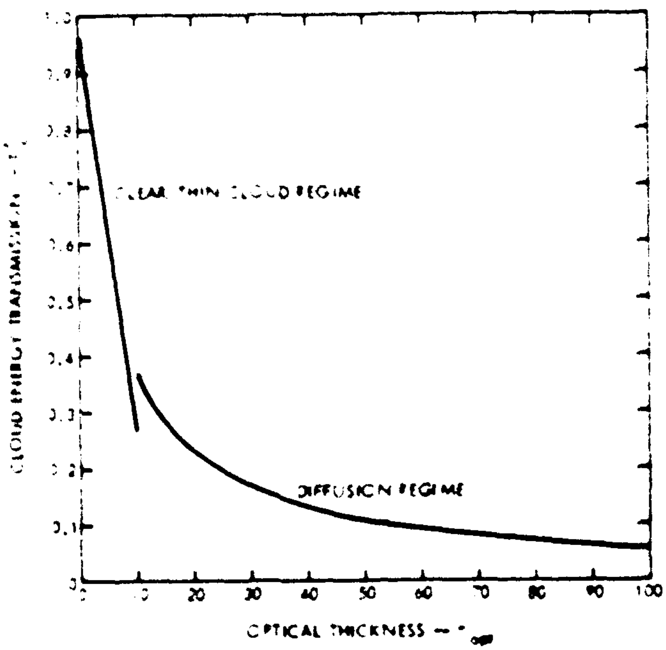


Figure 4-7. Typical Cloud Energy Transmission for Blue Skylight and Stellar Light ($\langle\cos\theta\rangle = 0.83$, $\omega_0 = 1.$)

4.3.3 Cloud to Water Energy Transmission - Noise

Because the sun and moon are effectively sources of infinite plane waves, and the blue sky and stellar background cover the entire hemisphere, there is no "spot" or "beam" enlargement in propagating from the cloud base to the water surface. Therefore, the transmission of noise energy from cloud base to the water surface is given by:

$$\boxed{\tau_{cw}' = 1,} \tag{4-7}$$

for all cloud conditions.

4.3.4 Air-Water Transmission - Noise

The energy transmission of the air-water interface is composed of two factors:

$$\tau'_{aw} = (\tau'_{aw\,1}) \times (\tau'_{aw\,2}) \tag{4-8}$$

for τ'_{aw} = Total energy transmission of air-water interface

$\tau'_{aw\,1}$ = air-water interface transmission due to index of refraction discontinuity

$\tau'_{aw\,2}$ = air water interface transmission due to foam and streaks on the sea surface.

This section treats $\tau'_{aw\,1}$, while $\tau'_{aw\,2}$ is discussed in Section 4.3.6. For thin clouds and clear weather ($\tau_{opt} \leq 10$) the solar and lunar energy transmission is again given as a function of wind speed and solar/lunar zenith angle in Table 4-5 and Figure 4-8.

For diffuse or uniform radiation incident on the sea-surface, we use the approximation in Section 3.3.4 (which neglects wave effects) and take $\tau'_{aw1} = 0.83$.

$$\boxed{\tau'_{aw\,1s} = 0.83, \quad \tau_{opt} \geq 10;} \tag{4-9}$$

$$\boxed{\tau'_{aw\,1m} = 0.83, \quad \tau_{opt} \geq 10;} \tag{4-10}$$

and for blue sky

$$\boxed{\tau'_{aw\,1B} = 0.83, \text{ all values of } \tau_{opt}.} \tag{4-11}$$

and for stellar zodiacal light,

$$\boxed{\tau'_{aw\,1Z} = 0.83, \text{ all values of } \tau_{opt}} \tag{4-12}$$

Table 4-5. $\tau'_{awls}/\tau'_{awlm}$ Time Averaged Downlink Air Sea Interface Transmittance (for Thin Clouds, $\tau_{opt} \leq 10$)

θ_1 Signal Zenith Angle in Air	V_1 Wind Speed								
	0	1.03	2.06	4.12	7.21	10.3	13.4	16.5	19.6 m/sec
	0	2	4	8	14	20	26	32	38 knots
0	0.979	0.977	0.976	0.974	0.970	0.967	0.963	0.960	0.956
5	0.975	0.974	0.972	0.970	0.966	0.963	0.959	0.956	0.952
10	0.964	0.962	0.961	0.958	0.955	0.951	0.948	0.944	0.941
15	0.945	0.944	0.943	0.940	0.936	0.933	0.929	0.926	0.922
20	0.920	0.918	0.917	0.914	0.910	0.907	0.903	0.899	0.896
25	0.887	0.885	0.884	0.881	0.877	0.873	0.870	0.866	0.863
30	0.847	0.846	0.844	0.841	0.837	0.833	0.829	0.826	0.822
35	0.800	0.798	0.797	0.794	0.790	0.786	0.782	0.779	0.775
40	0.747	0.745	0.743	0.741	0.736	0.733	0.729	0.725	0.722
45	0.687	0.686	0.684	0.681	0.677	0.673	0.669	0.666	0.663
50	0.620	0.619	0.617	0.615	0.611	0.608	0.605	0.602	0.599
55	0.548	0.546	0.545	0.543	0.540	0.538	0.536	0.534	0.532
60	0.469	0.468	0.468	0.466	0.465	0.464	0.464	0.464	0.463
65	0.385	0.385	0.385	0.386	0.387	0.389	0.391	0.393	0.396
70	0.295	0.298	0.299	0.303	0.310	0.315	0.321	0.325	0.329
75	0.203	0.209	0.214	0.224	0.236	0.247	0.255	0.262	0.268
80	0.113	0.126	0.136	0.153	0.172	0.186	0.197	0.206	0.213
85	0.0381	0.0610	0.0751	0.0968	0.119	0.135	0.148	0.157	0.166
90	0	0.0205	0.0390	0.0584	0.0800	0.0861	0.108	0.117	0.124

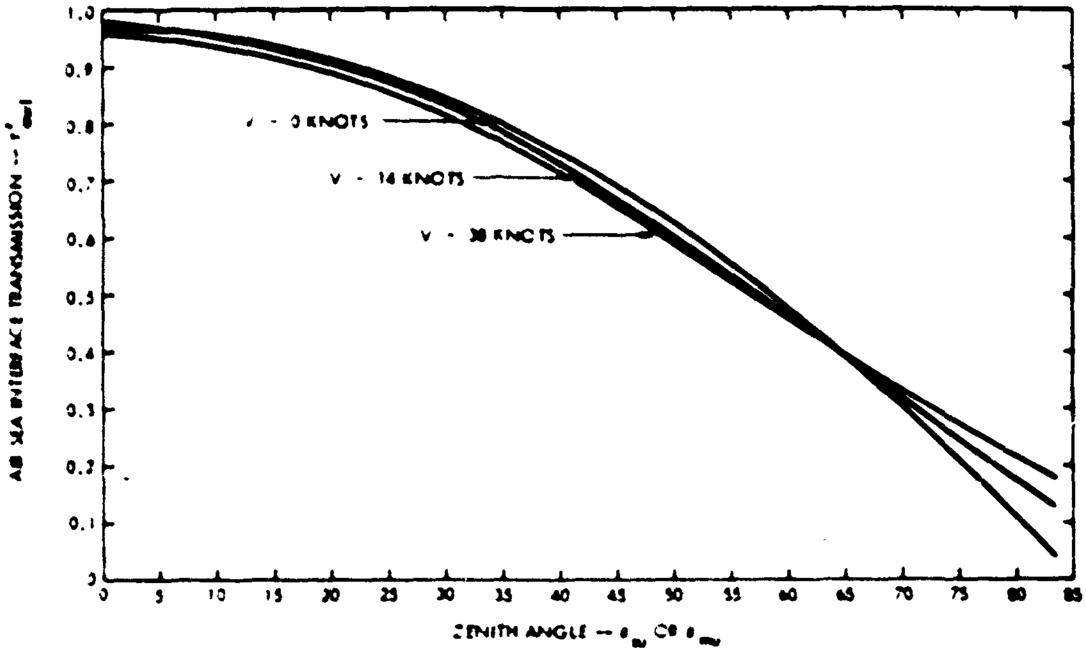


Figure 4-8. Air-Sea Interface Transmittance as a Function of Sun or Moon Zenith Angle and Surface Wind Speed V

4.3.5 Air-Water Interface Angular Effects - Noise

The wave slopes on the sea surface cause an overall increase in the beam divergence of an incident beam, or, equivalently, the apparent angular size of the source as viewed from an underwater point-of-view. With regard to the background sources, only the sun and moon for clear weather conditions ($\tau_{opt} \leq 10$) will be appreciably affected.

Again, using the Karp model discussed in Section 3.3.5,

$$\Delta\theta_{aw}^{su,mu} = 0.0103\ V^{1/2},\ (\tau_{opt} \leq 10) \tag{4-13a}$$

for $\Delta\theta_{aw}^{su}$ = RMS induced half-angle spread for the sun;

$\Delta\theta_{aw}^{mu}$ = RMS induced half-angle spread for the moon.

V = surface wind speed in knots.

For all τ_{opt},

$$\Delta\theta_{aw}^{B,Z} = 0, \tag{4-14}$$

for $\Delta\theta_{aw}^{B}$ = effect on blue sky source;

$\Delta\theta_{aw}^{Z}$ = effect on stellar/zodiacal source

Also $$\boxed{\Delta\theta_{aw}^{su,mu} = 0,\ (\tau_{opt} \geq 10)} \tag{4-13b}$$

since the light is diffuse after emerging from the thick clouds.

Tables 4-6 and Figure 4-9 evaluate (4-13a) for V in knots (and meters per second).

Since the full angular subtense of the sun (and the moon) is ≈0.5 degres, this effect will substantially increase its apparent size. The relative contribution of $\Delta\theta_{aw}$ to the distribution of noise radiance at the receiver is discussed in Section 4.3.8. Except for the clearest water it is a small effect, and so the impact of neglecting zenith angle effects, and dissimilar wave slopes in the downwind and crosswind direction, may be negligible. We therefore adopt this model until better information is available.

Table 4-6. RMS Air-Water Interface Induced Half-Angle Effects ($\tau_{opt} \leq 10$) Sun and/or Moon

V, Wind Speed		$\Delta\theta_{aw}$ su or mu	
Knots	Meters/Second	Milliradians	Degrees
0	0	0	0
2	1.03	14.6	0.84
4	2.06	20.7	1.18
8	4.12	29.2	1.67
14	7.21	38.6	2.21
20	10.3	46.2	2.65
26	13.4	52.6	3.0
32	16.5	58.4	3.35
38	19.6	63.6	3.64

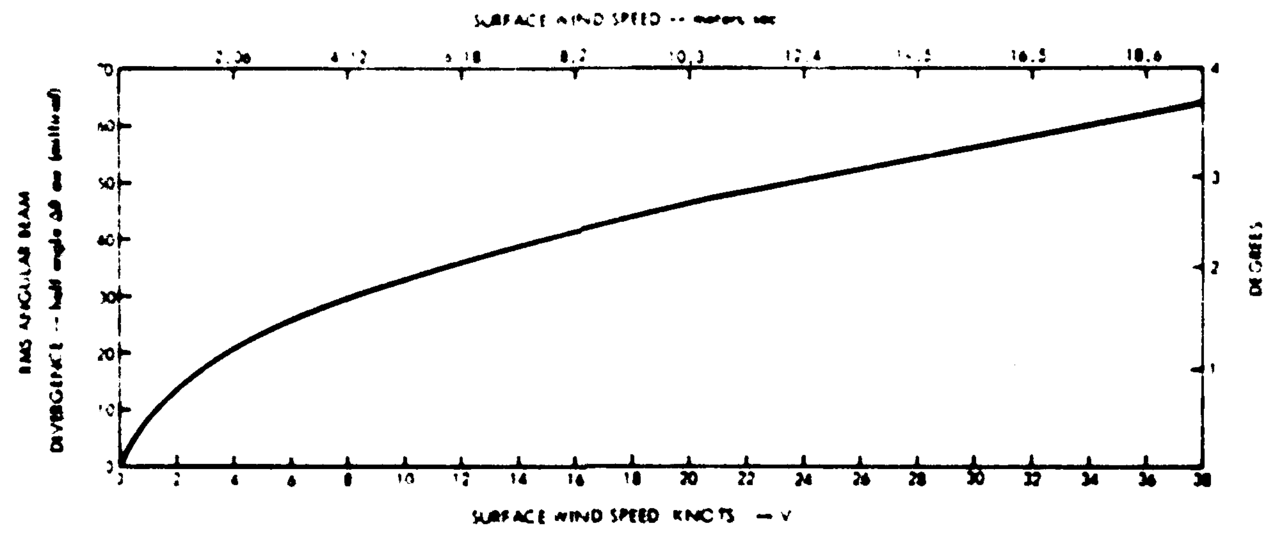


Figure 4-9. RMS Air-Water Interface Effect as a Function of Wind Speed V

4.3.6 Relative Surface Foam Coverage

The energy transmission of the air-water interface is composed of two factors:

$$\tau'_{aw} = (\tau'_{aw\,1}) \times (\tau'_{aw\,2}),$$

for τ'_{aw} = Total energy transmission of the air-water interface

τ'_{aw1} = air water interface transmission due to index of refraction discontinuity

and τ'_{aw2} = air water interface transmission due to foam and streaks on the water surface.

This section treats τ'_{aw2}, while τ'_{aw1} has been treated in Section 4.3.4.

The surface foam coverage and its effects are taken to be independent of the noise source and cloud conditions. As discussed in Section 3.3.6, for a foam albedo = 1,

$$\boxed{\tau'_{aw2} = 1 - (1.2\,(10^{-5}))\,V^{3.3},\ V \le 9\ \text{m/sec},} \quad (4\text{-}15a)$$

and

$$\boxed{\tau'_{aw2} = 1 - (1.2\,(10^{-5}))\,V^{3.3}\,(0.225V - 0.99),\ V \ge 9\ \text{m/sec}.} \quad (4\text{-}15b)$$

for V = surface wind speed in meters/sec.

Equation (4-15a,b) is evaluated in Table 4-7 and Figure 4-10 for V in knots (and meters/second).

Although this model neglects zenith angle effects we shall adopt it pending further experimental work.

Table 4-7. Air Water Energy Transmission Due to Surface Foam and Streaks (Assuming a Foam/Streak Albedo = 1)

V, Wind Speed		τ'_{aw2}
Knots	Meters/Second	
0	0	1
2	1.03	1
4	2.06	1
8	4.12	1
14	7.21	0.99
20	10.3	0.96
26	13.4	0.87
32	16.5	0.66
38	19.6	0.25

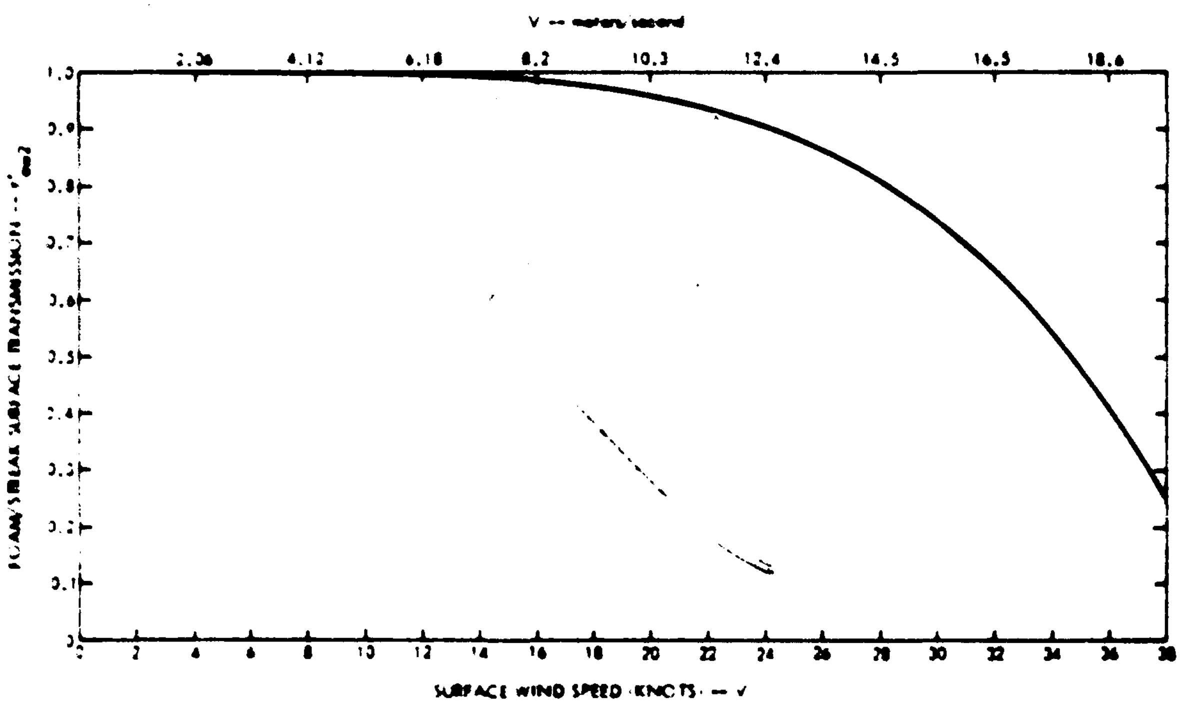


Figure 4-10. Foam/Streak Surface Coverage Transmission Versus Surface Wind Speed

4.3.7 Water Energy Transmission - Noise

The energy transmission of the water is denoted by τ_w'. The angularly localized noise sources (sun and moon) behave similarly to the signal energy transmission discussed in Section 3.3.7, thus we take:

$$\boxed{\begin{aligned} \tau'_{wsu} &= \exp - \left\{ \frac{\sum_{i=1}^{j} (k_i D_i)}{\cos \theta_{su}^{w}} \right\} && (4\text{-}16a) \\ \text{for} \quad \theta^{w}_{su} &= \sin^{-1} \left(\frac{1}{n} \sin \theta_{su} \right) \\ \text{and} \quad \sum_{i=1}^{j} D_i &= D, \quad \tau_{opt} \le 10. \end{aligned}}$$

where k_i = diffuse attenuation coefficient for the i'th water layer;

D_i = thickness of the i'th water layer

D = receiver depth

n = sea-water index of refraction

θ_{su}^{w} = in-water solar zenith angle

θ_{su} = in-air solar zenith angle;

$$\boxed{\begin{aligned} \text{and} \quad \tau'_{wmu} &= \exp - \left\{ \frac{\sum_{i=1}^{j} (k_i D_i)}{\cos \theta_{mu}^{w}} \right\} && (4\text{-}17a) \\ \text{for} \quad \theta^{w}_{mu} &= \sin^{-1} \left(\frac{1}{n} \sin \theta_{mu} \right) \\ \text{and} \quad \sum_{i=1}^{j} D_i &= D, \quad \tau_{opt} \le 10. \end{aligned}}$$

where θ_{mu}^{w} = in-water lunar zenith angle;

θ_{mu} = in-air lunar zenith angle.

4.3.7 (Continued)

Moreover for the thick cloud conditions,

$$\tau'_{wsu} = \exp - \left\{ \sum_{i=1}^{j} k_i D_i \right\}, \text{ for } \tau_{opt} > 10. \tag{4-16b}$$

and, in the same way

$$\tau'_{wru} = \exp - \left\{ \sum_{i=1}^{j} k_i D_i \right\}, \text{ for } \tau_{opt} > 10. \tag{4-17b}$$

For the blue sky and starlight/zodiacal light background sources, the same models should approximately apply for all τ_{opt}. Therefore,

$$\tau'_{WB} = \exp - \left\{ \sum_{i=1}^{j} k_i D_i \right\}, \text{ for all } \tau_{opt}. \tag{4-18}$$

and

$$\tau'_{WZ} = \exp - \left\{ \sum_{i=1}^{j} k_i D_i \right\}, \text{ for all } \tau_{opt}. \tag{4-19}$$

This model is uncertain in

(1) The values of k_i to use;

(2) The values of D_i;

(3) Its applicability in very clear water and/or at shallow receiver depths.

It is the best model available now and it will be revised when better information becomes available.

4.3.8 Water Distribution of Radiance - Noise

There is no experimentally verified expression for the in-water distribution of background radiance as a function of source character, source zenith angle, water properties and receiver depth. As discussed in Section 3.3.8, we therefore adopt the expression

$$1 - \left(\frac{\sin \theta^{w}}{\sin \theta_0}\right)^2$$

as an estimate of the angular distribution, with

θ^{w} = in-water angle measured from the axis, or principal ray of the noise source.

θ_0 is related to the half power point of the received radiance by the equation

$$\boxed{\frac{1}{2} = \frac{1-(\cos \theta_{1/2}) - \dfrac{1}{3 \sin^2 \theta_0}\left\{\cos(\theta_{1/2}) \sin^2(\theta_{1/2}) + 2 \cos(\theta_{1/2}) - 2\right\}}{1 - \cos \theta_0 - \dfrac{1}{3 \sin^2 \theta_0}\left\{\cos \theta_0 \sin^2 \theta_0 + 2 \cos \theta_0 - 2\right\}}.} \qquad (4\text{-}20a)$$

Equation (4-20a) is evaluated in Table 4-8. Values between those shown are obtained by linear interpolation.

Again assuming that the in-air incident beam spread, air-water beam spread and in-water scattering induced spread are <u>statistically</u> independent effects, we adopt the NOSC[1] model:

$$\boxed{\theta_{1/2} = \left[f_w + f_{aw} + f_a\right]^{1/2}.} \qquad (4\text{-}20b)$$

for all four out-of-water background sources. For solar and lunar sources

$$\boxed{\begin{aligned} f_w &= \text{water contribution} \\ &= \sigma_{sl}^2 \frac{s\,D}{\cos \theta^{w}_{su}}, \quad \text{all } \tau_{OPT} \end{aligned}} \qquad (4\text{-}21a)$$

Table 4-8. Relation of radiance zero point, θ_0, and received radiance half-power point, $\theta_{1/2}$, for $1 - (\sin \theta^w/\sin \theta_0)^2$ radiance distribution

$\theta_{1/2}$ (degrees)	$\theta_{1/2}$ (degrees)
3.8	5
7.6	10
11.4	15
15.2	20
19.0	25
22.7	30
26.5	35
30.2	40
33.9	45
37.5	50
41.1	55
44.6	60
48.1	65
51.6	70
54.9	75
58.2	80

4.3.8 (Continued)

and

$$\boxed{f_w = \langle\theta^2_{si}\rangle \frac{sD}{\cos \theta^w_{mu}}, \text{ all } \tau_{OPT}} \tag{4-22a}$$

while for the distributed background sources of blue sky and stellar/zodiacal light,

$$\boxed{f_w = \langle\theta_{si}^2\rangle sD, \text{ all } \tau_{OPT}} \tag{4-23a}$$

for $\langle\theta^2_{si}\rangle$ = mean square single scattering angle in water

s = scattering coefficient in water

D = receiver depth

θ^w_{su} = in-water solar zenith angle

θ^w_{mu} = in-water lunar zenith angle.

4.3.8 (Continued)

Again, for solar and lunar sources

$$\boxed{\begin{aligned} f_{aw} &= (0.0103\ V^{1/2})^2\ ;\quad \tau_{OPT} \leq 10 \qquad &(4\text{-}21b),\ (4\text{-}22b)\\ &= 0\ ;\ \tau_{OPT} \geq 10. \qquad &(4\text{-}21c),\ (4\text{-}22c)\end{aligned}}$$

V = surface wind speed (knots), as discussed in Section 4.3.5.

For the distributed sources,

$$\boxed{f_{aw} = 0,\ \text{all}\ \tau_{OPT}} \qquad (4\text{-}23b)$$

Finally, for the sun and moon,

$$\boxed{\begin{aligned} f_a &= \left(\frac{1}{n}\right)^2 \left(\theta_{s/2}\right)^2;\quad \tau_{OPT} \leq 10 \qquad &(4\text{-}21d)\\ &= (33.8°)^2,\quad \tau_{OPT} \geq 10 \qquad &(4\text{-}21e)\end{aligned}}$$

and

$$\boxed{\begin{aligned} f_a &= \left(\frac{1}{n}\right)^2 \left(\theta_{m/2}\right)^2;\quad \tau_{OPT} \leq 10; \qquad &(4\text{-}22d)\\ &= (33.8°)^2;\quad \tau_{OPT} \geq 10. \qquad &(4\text{-}22e)\end{aligned}}$$

for n = water index of refraction,

$\theta_{s/2}$ = half the angular substense of the sun (~(1/4)°)

and $\theta_{m/2}$ = half the angular substense of the moon (~(1/4)°)

These equations have been discussed and derived in Section 3.3.8. For the distributed sources,

$$f_a = (33.8°)^2 \quad ,\ \text{all}\ \tau_{opt}.$$

4.3.8 (Continued)

In general, the receiver will be directly viewing the signal, while the background source enters at an off-axis angle. Then the fraction of the noise radiance which enters the receiver is given by

$$f(\theta_0, \theta_R, \psi) = \frac{\int_0^{2\pi} d\phi \int_0^{\theta_R} d\theta^w \sin\theta^w \left[1 - \left(\frac{\sin\theta^{w'}}{\sin\theta_0}\right)^2\right]}{\int_0^{2\pi} d\phi \int_0^{\theta_0} d\theta^w \sin\theta^w \left[1 - \left(\frac{\sin\theta^{w}}{\sin\theta_0}\right)^2\right]} \qquad (4\text{-}24a)$$

for $$\theta^{w'} = \cos^{-1}\left[\cos\theta^w \cos\psi + \sin\theta^w \sin\psi \sin\phi\right],$$

for θ_R = half-angle of the receiver field of view

ψ = off-set angle between axis of noise source and receiver optical axis.

This expression will be used further in Section 4.2.10 and 4.2.11.

(4-24a) applies to the background sources in thin cloud conditions. Under thick cloud conditions, both signal and background will appear to arrive from the zenith, and so $\psi \to 0$. For this case,

$$f(\theta_0, \theta_R) = \frac{1 - \cos\theta_R - \frac{1}{3\sin^2\theta_0}\left[\cos\theta_R \sin^2\theta_R + 2\cos\theta_R - 2\right]}{1 - \cos\theta_0 - \frac{1}{3\sin^2\theta_0}\left[\cos\theta_0 \sin^2\theta_0 + 2\cos\theta_0 - 2\right]} \qquad (4\text{-}24b)$$

References for Section 4.3.8

1. R.E. Howarth, M.E. Hyde and W.R. Stone, "Submarine-Aircraft and Submarine-Satellite Optical Communications System Model (U)," Confidential Report, NELC-TR-2021, 1977.

4.3.9 Detection Bandwidth

The required electrical detection bandwidth to optimally detect the pulses discussed in Section 3.3.9 is not known at present. In lieu of such a result we assume:

1) The receiver has foreknowledge of the expected pulse width;

2) $$\boxed{B = \frac{0.4}{(2.45\ t_m)}} \tag{4-25}$$

for B = electrical detection bandwith

t_m = time at which pulse peak value occurs after pulse start, for a pulse shape $f(t) = t \exp - (t/t_m)$.

For gaussian shaped pulses and detection filter, (4-25) is the nearly optimum match.* As further work is done in the area of the real pulses to be expected here, (4-25) may be revised.

Equation 4-25 is evaluated in Table 4-9 and Figure 4-11 for the pulse-widths and optical thicknesses developed in Section 3.3.9.

Table 4-9. Typical Detection Bandwidths for Pulse Width Conditions of Table 3-11

τ_{opt}, Optical Thickness	T Geom. Thickness (km)	Δt_c Pulsewidth (μsec)	Δt_M Peak Time (μsec)	B Detection Bandwidth (kHz)
10	0.25	1.15	0.47	348
20	0.5	3.55	1.49	110
30	0.75	7.08	2.89	56.5
40	1.00	11.27	4.6	35.5
50	1.25	16.13	6.58	24.8
60	1.50	21.55	8.8	18.6
70	1.75	27.48	11.22	14.6
80	2.00	33.93	13.85	11.8
90	2.25	40.88	16.69	9.8
100	2.50	48.25	19.7	8.3

*H.P. Westman, Editor, Reference Data for Radio Engineer, Fifth Edition, p. 29-5, (H. W. Sams & Co., New York, 1969).

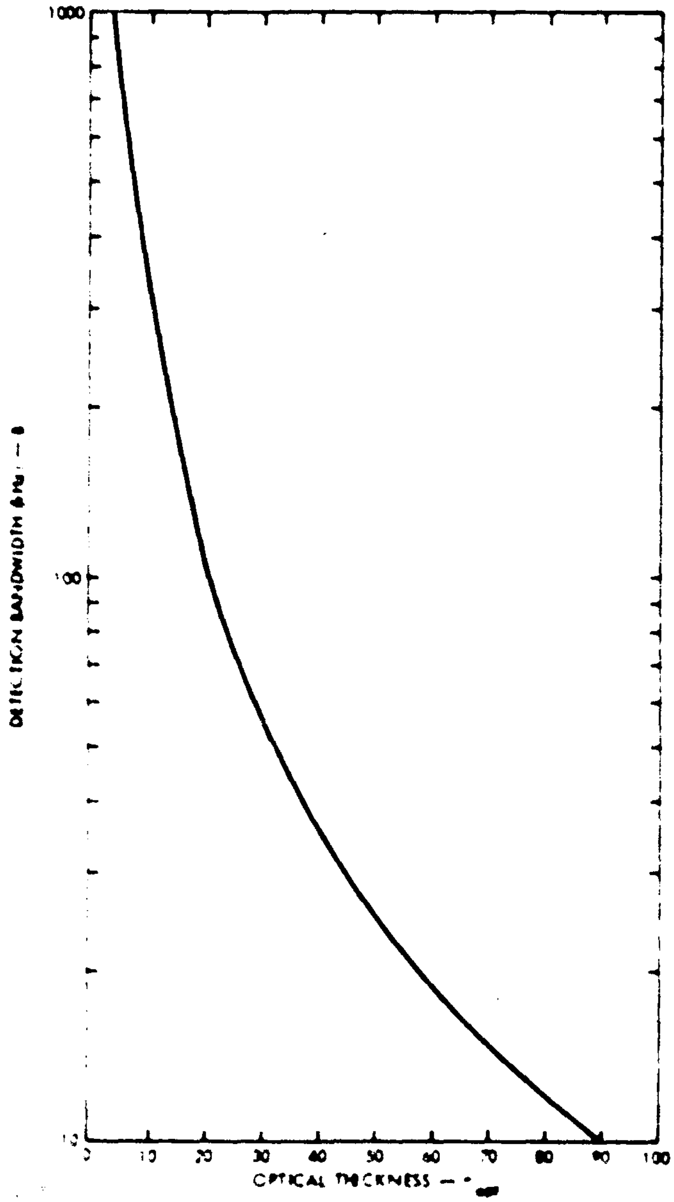


Figure 4-11. Detection Bandwidth for Pulse-Widths of Table 3-11

4.3.10 Average Background Power Due to Sunlight

The average optical background power in the receiver due to the sun is given by an equation analogous to that developed in Section 3.3.10 for the received optical signal energy. We therefore take

$$
\begin{aligned}
P_{su} = \; & \text{(Spectral Radiance at Receiver Aperture Due to Sun)} \times \\
& \text{(Receiver optics transmission)} \times \text{(Receiver Area)} \times \\
& \text{(Receiver optical filter banpass)} \times \text{(Receiver Solid Angle)} \times \\
& \text{(Fraction of incident radiance in this receiver field of view).}
\end{aligned}
\tag{4-26}
$$

We take

τ_R = Receiver optics transmission

d = Receiver aperture diameter

$\frac{\pi d^2}{4}$ = Area of receiver aperture

B_{opt} = Receiver optical filter bandpass

θ_R = Half-Angle of the receiver field of view

$2\pi(1-\cos\theta_R)$ = Receiver field of view solid angle

L_{su} = Spectral Radiance at Receiver aperture due to the sun

and

$f'(\theta_0, \theta_R, \psi)$ = fraction of incident radiance within receiver field of view.

Then

$$
\boxed{P_{SU} = L_{SU}\left(\tau_R \frac{\pi d^2}{4}\right) B_{opt}\left(2\pi\,(1-\cos\theta_R)\right) f'(\theta_0, \theta_R, \psi).}
\tag{4-27}
$$

Because the sun is a CW source, we use the energy transmission formalism to develop the expression:

4.3.10 (Continued)

L_{su} = (Exo-atmospheric effective solar radiance) X
(Clear Atmosphere Energy Transmission) X (Cloud Energy Transmission) X
(Cloud to Water Energy Transmission) X
(Air-Water Interface Energy Transmission) x (Water Energy Transmission),

(4-28)

and we use

L_s = Exo-atmospheric effective solar radiance

τ_a' = Clear atmosphere energy transmission, as discussed in Section 4.3.1;

τ_{cs}' = Cloud energy transmission, as discussed in Section 4.3.2;

τ_{cw}' = Cloud to water energy transmission, as discussed in Section 4.3.3;

τ_{aws}' = Air-water energy transmission, as discussed in Sections 4.3.4 and 4.3.6;

τ_{wsu}' = Water energy transmission, as discussed in Section 4.3.7.

Gathering these expressions we find

$$\boxed{L_{su} = L_s \tau_a' \tau_{cs}' \tau_{cw}' \tau_{aws}' \tau_{wsu}'} \quad (4\text{-}29)$$

The fraction of incident radiance within the receiver field of view depends on the angular separation between the axis of the receiver field of view and the in-water solar zenith angle, as developed in Section 4.3.8.

4.3.10 (Continued)

$$f'(\theta_R, \phi_0, \delta) = \frac{\int_0^{2\pi} d\theta \int_0^{\theta_R} d\,\phi^w \sin \phi^w \left[1- \left(\frac{\sin \phi^{w'}}{\sin \phi_0}\right)^2\right]}{\int_0^{2\pi} d\theta \int_0^{\phi_0} d\phi^w \sin \phi^w \left[1- \left(\frac{\sin \phi^w}{\sin \phi_0}\right)^2\right]} \quad (4\text{-}30)$$

$$\text{for} \quad \phi^{w'} = \cos^{-1}\left\{\cos \phi^w \cos \delta_{SUR} + \sin \phi^w \sin \delta_{SUR} \sin \theta\right\} \quad (4\text{-}31)$$

and δ_{SUR} = angular separation between solar beam axis and receiver optical axis,

ϕ_0 = off solar beam axis angle at which the solar radiance goes to zero.

These expressions will be used in the development of the Noise Equivalent Power expression in Section 4.3.15.

4.3.11 Average Background Power Due to Moonlight

The average optical background power in the receiver due to the moon is completely analogous to that for the sun discussed in Section 4.3.10. We therefore take

P_{mu} = (Spectral Radiance at Receiver Aperture Due to Moon) X
(Receiver optics transmission) X (Receiver area) X
(Receiver optical filter bandpass) X (Receiver Solid Angle) X
(Fraction of incident radiance within the receiver field of view). (4-32)

We take τ_R = Receiver optics transmission,

d = Receiver aperture diameter,

$\frac{\pi d^2}{4}$ = Area of receiver aperture,

B_{opt} = Receiver optical filter bandpass,

θ_R = Half-Angle of the Receiver Field of View

$2\pi(1 - \cos\theta_R)$ = Receiver field of view solid angle

L_{mu} = Spectral radiance at receiver aperture due to moon

and

$f'(\phi_O, \theta_R, \delta)$ = Fraction of incident radiance within receiver field of view.

Then

$$\boxed{P_{mu} = L_{mu}\left(\tau_R \frac{\pi d^2}{4}\right)\left(B_{opt}\right)\left(2\pi(1 - \cos\theta_R)\right) f'(\phi_O, \theta_R, \delta)} \tag{4-33}$$

4.3.11 (Continued)

Because the moon is a CW source, we use the energy transmission formalism to develop the expression:

L_{mu} = (Exo-atmospheric effective lunar radiance) X
(Clear atmosphere energy transmission) X (Cloud energy transmission) X
(Cloud to water energy transmission) X
(Air-Water interface energy transmission) X
(Water energy transmission), (4-34)

and we use

L_m = Exo-atmospheric effective lunar radiance;

τ_a' = Clear atmosphere energy transmission, as discussed in Section 4.3.1

τ_{cm}' = Cloud energy transmission, as discussed in Section 4.3.2.

τ_{cw}' = Cloud to water energy transmission, as discussed in Section 4.3.3

τ_{awm}' = Air-Water energy transmission as discussed in Section 4.3.4, and 4.3.6.
and

τ_{wmu}' = Water energy transmission, as discussed in Section 4.3.7.

Gathering the various expressions we find

$$\boxed{L_{mu} = L_m \tau_a' \tau_{cm}' \tau_{cw}' \tau_{awm}' \tau_{wmu}'} \tag{4-35}$$

As for the sunlight, the fraction of incident lunar radiance within the receiver field of view depends on the angular separation between the optical axis of the receiver field of view and the in-water lunar zenith angle. As developed in Section 4.3.8,

4.3.11 (Continued)

$$f'(\theta_R, \theta_0, \delta) = \frac{\int_0^{2\pi} d\theta \int_0^{\theta_R} d\theta^w \sin \theta^w \left[1 - \left(\frac{\sin \theta^{w'}}{\sin \theta_0}\right)^2\right]}{\int_0^{2\pi} d\theta \int_0^{\theta_0} d\theta^w \sin \theta^w \left[1 - \left(\frac{\sin \theta^w}{\sin \theta_0}\right)^2\right]} \tag{4-36}$$

for

$$\theta^{w'} = \cos^{-1}\left\{\cos \theta^w \cos \delta_{MUR} + \sin \theta^w \sin \delta_{MUR} \sin \theta\right\} \tag{4-37}$$

and

δ_{MUR} = Angular separation between lunar beam axis and receiver optical axis

θ_0 = Off lunar beam axis angle at which the lunar radiance goes to zero.

These expressions will be used in the development of the Noise Equivalent Power expression in Section 4.3.15.

4.3.12 Average Background Power Due to Blue Skylight

The average optical background power in the receiver due to the blue skylight is partially analogous to that for the sun and moon discussed in Sections 4.3.10 and 4.3.11. We therefore take, for the average optical background power due to blue skylight:

P_{BS} = (Spectral Radiance at Receiver Aperture due to the Blue Sky) X
(Receiver optics transmission) X (Receiver area) X
(Receiver optical filter bandpass) X (Receiver solid angle) X
(Fraction of incident radiance within the receiver field of view).

(4-38)

We take

τ_R = Receiver optics transmission;

d = Receiver aperture diameter;

$\frac{\pi d^2}{4}$ = Area of receiver aperture;

B_{opt} = Receiver optical filter bandpass

θ_R = Half-Angle of the Receiver field of view

$2\pi(1 - \cos\theta_R)$ = Receiver field of view solid angle

L_{BS} = Spectral radiance at receiver aperture due to the blue skylight,

$f'(\theta_0, \theta_R, \phi)$ = Fraction of incident radiance within receiver field of view,

and

$$\boxed{P_{BS} = L_{BS}\left(\tau_R\left(\frac{\pi d^2}{4}\right)\right) B_{opt}\, 2\pi\,(1 - \cos\theta_R)\, f'(\theta_0, \theta_R, \phi)} \qquad (4\text{-}39)$$

Because the blue skylight is a cw source, we use the energy transmission formalism to develop the expression:

L_{BS} = (Clear sky exo-atmospheric effective radiance) X
(Clear atmospheric transmission) X (Cloud energy transmission) X
(Cloud to Water Energy Transmission) X
(Air-Water Interface Energy Transmission) X (Water Energy Transmission)

(4-40)

4.3.12 (Continued)

and we use

L_B = Clear sky exo-atmospheric effective radiance,

τ_a' = Clear atmospheric transmission, as discussed in Section 4.3.1,

τ_{CB}' = Cloud energy transmission, as discussed in Section 4.3.2,

τ_{CW}' = Cloud to water energy transmission as discussed in Section 4.3.3,

τ_{awB}' = Air-water energy transmission, as discussed in Sections 4.3.4 and 4.3.6,

τ_{wB}' = Water energy transmission, as discussed in Section 4.3.7.

Gathering the expressions we find

$$\boxed{L_{BS} = L_B\, \tau_a'\, \tau_{cb}'\, \tau_{cw}'\, \tau_{awB}'\, \tau_{wB}'} \tag{4-41}$$

Again, the fraction of blue-sky radiance within the receiver field of view is given by

$$f'(\theta_R, \theta_0, [illegible]) = \frac{\displaystyle\int_0^{2\pi} d\phi \int_0^{\theta_R} d\theta^w \sin\theta^w \left[1-\left(\frac{\sin\theta^{w'}}{\sin\theta_0}\right)^2\right]}{\displaystyle\int_0^{2\pi} d\phi \int_0^{\theta_0} d\theta^w \sin\theta^w \left[1-\left(\frac{\sin\theta^w}{\sin\theta_0}\right)^2\right]}, \tag{4-42}$$

$$\boxed{\text{for } \theta^{w'} = \cos^{-1}\left[\cos\theta^w \cos\theta_{BR} + \sin\theta^w \sin\theta_{BR} \sin\phi\right]} \tag{4-43}$$

4.3.12 (Continued)

and δ_{BR} = Off zenith pointing angle of the receiver axis,
while

θ_0 = Off-zenith angle at which the blue sky radiance goes to zero.

These expressions will be used in the development of the Noise Equivalent Optical Power expression in Section 4.3.15.

4.3.13 Average Background Power Due to Stellar/Zodiacal Light

The average optical background power in the receiver due to the nighttime distributed sources of stellar and zodiacal light follows the patterns established in the previous three sections. We take, for the average optical background power due to these sources:

P_Z = (Spectral radiance at receiver aperture due to the stellar/Zodiacal light) X (Receiver optics transmission) X (Receiver Area) X (Receiver optical filter bandpass) X (Receiver solid angle) X (Fraction of incident radiance within the receiver field-of-view). (4-44)

We again take

τ_R = Receiver optics transmission,

d = Receiver aperture diameter,

$\frac{\pi d^2}{4}$ = Area of receiver aperture,

B_{OPT} = Receiver optical filter bandpass;

θ_R = Half-Angle of the receiver field-of-view;

$2\pi (1-\cos \theta_R)$ = Receiver field-of-view solid angle;

L_{ZS} = Spectral radiance at receiver aperture due to the stellar/zodiacal light;

$f'(\phi_0, \theta_R, \xi)$ = Fraction of incident radiance within the receiver field-of-view;

ϕ_0 = Off-axis angle at which the received radiance goes to zero, as discussed in Section 4.3.8.

Then,

$$\boxed{P_Z = L_{ZS} \left(\tau_R \left(\frac{\pi d^2}{4} \right) \right) B_{OPT} \left(2\pi \left(1 - \cos \theta_R\right)\right) f'(\phi_0, \theta_R, \xi)} \qquad (4-45)$$

4.3.13 (Continued)

Because this background source is cw, we use the energy transmission formalism to develop the expression:

L_{ZS} = (Stellar/Zodiacal Light Clear Sky Effective Exo-Atmospheric Radiance) X (Clear Atmospheric Transmission) X (Cloud Energy Transmission) X (Cloud to Water Energy Transmission) X (Air-Water Interface Energy Transmission) X (Water Energy Transmission) (4-46)

and we use

L_Z = Stellar/Zodiacal Light Clear Sky Effective Exo-Atmospheric Radiance,

τ_a' = Clear Atmospheric Transmission, as discussed in Section 4.3.1,

τ_{cz} = Cloud Energy Transmission, as discussed in Section 4.3.2,

τ_{cw}' = Cloud to Water Energy Transmission, as discussed in Section 4.3.3,

τ_{awz}' = Air-Water Interface Energy Transmission, as discussed in Sections 4.3.4 and 4.3.6,

τ_{wz}' = Water Energy Transmission, as discussed in Section 4.3.7.

Gathering the expressions we find:

$$\boxed{L_{ZS} = L_Z \tau_a' \tau_{cz} \tau_{cw}' \tau_{awz}' \tau_{wz}'} \quad (4\text{-}47)$$

Again, the fraction of stellar/zodiacal radiance within the receiver field-of-view is given by

$$f(\theta_R, \theta_0) = \frac{\int_0^{2\pi} d\phi \int_0^{\theta_0} d\theta^w \sin\theta^w \left[1 - \left(\frac{\sin\theta^{w'}}{\sin\theta_0}\right)^2\right]}{\int_0^{2\pi} d\phi \int_0^{\theta_0} d\theta^w \sin\theta^w \left[1 - \left(\frac{\sin\theta^w}{\sin\theta_0}\right)^2\right]} \quad (4\text{-}48)$$

4.3.13 (Continued)

$$\text{for } \theta^{w'} = \cos^{-1}\left[\cos\theta^{w}\cos\delta_{zr} + \sin\theta^{w}\sin\delta_{zr}\sin\phi\right]$$

and δ_{zr} = Off-zenith pointing angle of the receiver axis.

These expressions will be used in the development of the Noise Equivalent Optical Power expression in Section 4.3.15.

4.3.14 Average Background Power Due to Bioluminescence

The final source of optical background power is the local bioluminescent sources which are stimulated to emit by the submarine motion, or other disturbances in the water. This is modelled in a slightly different way than the previous four sources, and cloud and water properties have only an indirect effect on this source strength. We therefore write for the average background power due to bioluminescence,

P_{BL} = (Spectral irradiance at receiver aperture due to bioluminescence) X (Receiver Optics Transmission) X (Receiver Area) X (Receiver Optical Filter Bandpass). (4-50)

and we set

L_{BL} = Spectral irradiance at receiver aperture due to bioluminescence,

τ_R = Receiver Optics Transmission,

d = Diameter of Receiver Aperture,

$\frac{\pi d^2}{4}$ = Area of Receiver Aperture,

B_{OPT} = Optical Filter Bandpass.

Therefore,

$$\boxed{P_{BL} = L_{BL}\left(\tau_R\left(\frac{\pi d^2}{4}\right)\right)B_{OPT}} \qquad (4\text{-}51)$$

4.3.15 Noise Equivalent Optical Power Dependence on Noise Sources

In general, a direct detection optical communication system has four independent noise contributions, which include thermal (or amplifier) noise, dark current detector noise, signal shot noise and background shot noise. These are noise sources insofar as they generate fluctuations in the electrical current present in the detection system. It is conventional to write the "noise" as the 1-σ point of the fluctuating electrical current, assuming the noise sources add independently and are steady in character.

Because we have derived a signal level in terms of the instantaneous received optical power, it is appropriate to describe the noise components in terms of a Noise Equivalent (Optical) Power, as derived from the post-detection electrical power.

We write, for a photomultiplier tube type of detector,

$$\boxed{NEP_{tot} = \left[NEP_{th}^2 + NEP_{dc}^2 + NEP_{ss}^2 + NEP_B^2\right]^{1/2}} \qquad (4\text{-}52)$$

for

NEP_{tot} = Total Noise Equivalent (Optical) Power due to all sources

NEP_{th} = Noise equivalent optical power due to thermal or amplifier noise

NEP_{dc} = Noise equivalent optical power due to photo-detector dark current

NEP_{ss} = Noise equivalent optical power due to shot-noise generated by the signal

NEP_B = Noise equivalent optical power due to shot-noise generated by the Background.

Then

$$\boxed{NEP_{TH} = \left[\frac{4\,(kT)\,B\,F_a}{G^2\left(\frac{\eta e}{h\nu}\right)^2 R_L}\right]^{1/2}} \qquad (4\text{-}53)$$

4.3.15 (Continued)

for

(kT) = thermal noise energy = (Boltzman's constant) X (Absolute Temperature)

B = electrical detection bandwidth, as discussed in Section 4.3.9

G = Detection gain

η = Photo surface quantum efficiency

e = charge on the electron

$h\nu$ = energy per signal photon

$\eta e/h\nu$ = photo-surface responsivity

R_L = load resistance

F_a = Amplifier noise figure.

For the dark current contribution,

$$NEP_{DC} = \left[\frac{2\ e\ B\ F\ G^2\ I_d\ R_L}{G^2\ (\eta e/h\nu)^2\ R_L}\right]^{1/2} = \left[\frac{2\ e\ B\ F\ I_d}{(\eta e/h\nu)^2}\right]^{1/2} . \tag{4-54}$$

for

F = excess noise in the detector gain

and I_d = dark current at the photo-cathode.

For the signal shot noise contribution,

$$NEP_{SS} = \left[\frac{2\ e\ B\ F\ (\eta e/h\nu)\ \ G^2 \hat{P}_R\ R_L}{G^2\ (\eta e/h\nu)^2\ R_L}\right]^{1/2} = \left[\frac{2\ e\ B\ F\ \hat{P}_R}{(\eta e/h\nu)}\right]^{1/2} \tag{4-55}$$

for $\hat{P}_R$ = peak received optical signal power at the photo surface, as discussed in Section 3.3.10.

Finally, the CW background contributes

4.3.15 (Continued)

$$\boxed{NEP_B = \left[\frac{2\,e\,B\,F\,G^2\,(\eta e/h\nu)\,R_L\,(\sum_i P_B^{\,i})}{G^2\,(\eta e/h\nu)^2\,R_L}\right]^{1/2} = \left[\frac{2\,e\,B\,F\,\sum_i P_B^{\,i}}{(\eta e/h\nu)}\right]^{1/2}} \qquad (4\text{-}56)$$

for

$$\boxed{\sum_i P_B^{\,i} = P_{su} + P_{mu} + P_{BS} + P_Z + P_{BL}\ .} \qquad (4\text{-}57)$$

for

P_{su} = Average background power due to sunlight, as discussed in Section 4.3.10;

P_{mu} = Average background power due to moonlight, as discussed in Section 4.3.11;

P_{BS} = Average background power due to blue skylight, as discussed in Section 4.3.12;

P_Z = Average background power due to stellar/zodiacal light, as discussed in Section 4.3.13;

and P_{BL} = Average background power due to bioluminescence, as discussed in Section 4.3.14.

Two comments are in order at this point:

1. If the signal shot noise dominates the noise components, the formulation should be re-examined to insure that enough photo-electrons are being generated to make it applicable;
2. Not all the average background contributors will be present at any one time, which will be accounted for in the time-of-day modeling of the respective spectral radiances.

GTE SYLVANIA

4.4 COMPUTER PROGRAM FOR COMPLETE SPDPM

4.4.1 Introduction

Figures 3-2 and 4-2 provided the basis for the computer program to perform calculations for the Single Pulse Downlink Propagation Model (SPDPM). The program is blocked out as shown in Figure 4-12.

Parameters which may be varied often are read from a data file, SPPM DATA. The values can be changed by editing this file.

The main program, SPPM, will display all parameter values prior to execution, then read parameter values for its use. Initial calculations are followed by a branch to one of the three cases: thin cloud, thick cloud, and clear atmosphere.

Within each case, signal calculations are performed first. This is followed by noise contributions from sun, moon, blue sky, stellar and zodiacal light, and bioluminescence. The final calculations include NEP's and the output follows.

There is a limited error message capability, primarily to handle cases where certain variables fall outside allowable limits.

Special functions can be used by all three cases. These include lookup tables and a numerical double integral.

4.4.2 Names of Variables

Because of the limitation of available characters in the FORTRAN IV programming language, many variables used in previous sections of this document required redefinition. Wherever possible, names were kept the same or very similar:

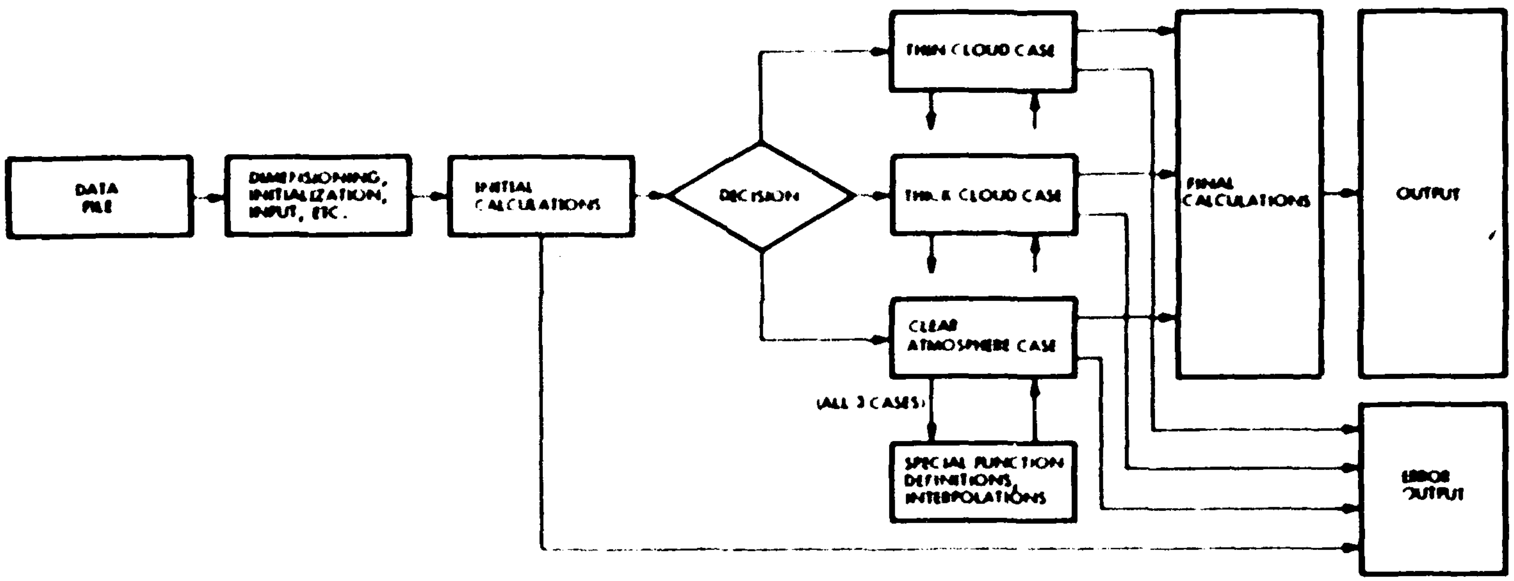


Figure 4-12. Complete SPDPM Computer Program Block Diagram

TEXT	PROGRAM	DEFINITION
c	C	Speed of light
I_d	ID	Photocathode dark current

Other variables were changed to a greater extent, but an attempt was made to make the new name easily understandable and relatable to the text name:

TEXT	PROGRAM	DEFINITION
B	BWE	Electrical Detection Bandwidth
B_{OPT}	BWOPT	Receiver Optical Filter Bandpass (Bandwidth)
D	DEPR	Receiver Depth

Because of the large number of text variables involving T, τ and θ, many of these required redefinition. First all angles ( ) were redefined to start with letters other than T (see below). Most program T variables are transmissions, with the following exceptions:

TEXT	PROGRAM	DEFINITION
T	TABS	Absolute Temperature
D_i	THWCI	i^{th} water layer thickness
T	THGC	Geometrical Cloud thickness
b	THOPTA	Effective Clear Atmosphere Optical Thickness
τ_{OPT}	THOPTC	Cloud Optical Thickness
t	TI	Time Variable
t_m	TIPEAK	Time of pulse peak, relative to pulse start

There are also several program internal variables beginning with T which have no couterpart in the text.

The large number of transmissions have led to a systematizaiton of these. They are all of the following form:

4.4.2 (Continued)

$$T\begin{pmatrix} A \\ \text{or} \\ AA \end{pmatrix}\begin{pmatrix} B \\ \text{or} \\ BB \end{pmatrix}\begin{pmatrix} C \\ \text{or} \\ \text{Nothing} \end{pmatrix}$$

where T signifies transmission; A or AA is a one or two letter designation for the energy source; B or BB, for the medium or interface; C, a further description if necessary.

A,AA	B, BB	C
SG - signal	A-air	F - foam + streaks on surface
S - Sun	C - Cloud	
M - moon	CW - Cloud to water	N - index of refraction
BS - Blue Sky	AW - Air Water Interface	
Z - Stellar/Zodiacal Light	W - Water	

Thus TSGAWN is transmission of the signal through the air-water interface considering refractive index effects; TZC is stellar/zodiacal light transmission through clouds. Text variables which correspond are τ_{awl} and τ_{cz}.

Angle variables have been renamed to begin with A for non-referenced angles, and ZA for Zenith Angles:

TEXT	PROGRAM	DEFINITION
θ	ASCAT	Cloud particle mean Scattering Angle
θ_{SU}	ZASA	Solar in-air zenith angle

Unfortunately, some variables had to be defined quite differently from text variables:

TEXT	PROGRAM	DEFINITION
$<\cos\theta>$	COSACS	Mean Cosine of in-Cloud Scattering Angle
$\eta\lambda/h\nu$	RESP	Responsivity
d	DIAR	Receiver aperture diameter

A list relating text and program variables follows:

A

ADLTA = δ =	Offset angle between receiver optical axis and axis of the incoming light (signal section)
ACSCAT = θ =	Cloud particle mean scattering angle
ATBWF = θ_T =	Full angle exp (-2) transmitter beamwidth
AMSW0 = θ^2_{S1} =	Mean square single scattering angle in water
ANSWI or ANSW(I) = θ^2_{S1i} =	Mean square single scattering angle in water for i'th layer
ARFOV = θ_R =	Half angle of the receiver field of view
AS = $\gamma_{S/2}$ =	Half of the angle subtended by the sun
AM = $\gamma_{M/2}$ =	Half of the angle subtended by the moon
ARDWSG = θ_0 =	Off-axis angle at which in-water radiance goes to zero
ABKHP =	Half-power angle of the background radiance
ADLTAS = δ ADLTAM = δ ADLTAB = δ ADLTAZ = δ	Offset angle between receiver optical axis and axis of the incoming light
ARDWNS,M,B,Z = θ_0 =	Off-axis angle at which in-water radiance goes to zero (noise section)

B

BWE = B =	Electrical detection bandwidth
BWOPT = B_{OPT} =	Receiver optical filter bandpass

C

CF = C_f =	Fraction of sea surface covered by foam and streaks
C = C =	Speed of light
COSACS = $\langle \cos\theta \rangle$ =	mean cosine of the in-cloud scattering angle

D

DEPR = D = Receiver depth

DIAR = d = Diameter of receiver aperture

DPWW = Δt_w = Pulse width due to water portion of the path

DPWCW = Δt_{cw} = Pulse width due to cloud to water portion of the path

DPWC = Δt_c = pulse width due to cloud portion of the path

E

EPNORM = A_E = Energy to instantaneous power normalization parameter

ER = E_R = Total received energy per pulse

E2 = E_2 = Exponential integral

ET = E_p = Transmitted energy per pulse

EXTC = $\cdot_c$ = Mean extinction coefficient of the cloud

F

FW = f_w = Water contribution to received beam half-angle

FAW = f_{aw} = Air/water interface contribution to received beam half-angle

FA = f_a = Atmospheric contribution to received beam half-angle

FWI or FW(I) = f_{wi} = Contribution of i'th water layer to received beam half-angle

FSG = $\dfrac{f'(\theta_0, \theta_R)}{f'(\theta_0, \theta_R, \theta_{SU})}$ = Fraction of incident radiance within receiver field of view

FWS0, FWM0, FWBS0, FWZ0 = f_w = Noise water contribution to received beam half-angle

FAS, FAM, FABS, FAZ = f_f Noise atmospheric contribution to received beam half-angle

F (Continued)

FAWS, FAWM, FAWBS, FAWZ = f_{aw} = Noise-air-water contribution to received beam half-angle

FNS, FNM, FNBS, FNZ (noise) = Fraction of incident radiance within receiver field of view

G

G = G = Detection gain

GAMT = γ_T = Transmitter optics transmission

GAMR = γ_R = Receiver optics transmission

H

HCW = H Distance from cloud base to water surface

HNU = $h\nu$ = Energy per signal photon

I

IRADW = $I(:^w)$ = Water radiance distribution

ID = I_d = Dark current at the photo cathode

J

J = j = Number of water layers present from surface to submarine receiver

K

KØ = k = Diffuse attenuation coefficient of the water

KI or K(I) = k_i = Diffuse attenuation coefficient of the i'th water layer

KT = (kt) = Thermal noise energy - (Boltzmann's constant) x (absolute temperature)

KBOLTZ = Boltzmann's constant

L

LSR = L_{SU} =	Spectral radiance at receiver aperture due to the sun
LSX = L_S =	Exo-atmospheric effective solar radiance
LMR = L_{MU} =	Spectral radiance at receiver aperture due to the moon
LMX = L_M =	Exo-atmospheric effective lunar radiance
LBSR = L_{BS} =	Spectral radiance at receiver aperture due to blue sky light
LBSX = L_B =	Clear sky exo-atmospheric effective radiance due to blue sky light
LZR = L_{ZS} =	Spectral radiance at receiver aperture due to stellar and zodiacal light
LZX = L_Z =	Clear sky exo-atmospheric effective radiance due to stellar and zodiacal light
LBLR = L_{BL} =	Spectral irradiance at receiver aperture due to bioluminescence

M

N

NOISF = F =	Excess noise in detector gain
NOISFA = F_a =	Amplifier noise figure
NDEX = n =	Water index of refraction
NEPTOT = NEP_{TOT} =	Total noise equivalent optical power due to all sources
NEPTH = NEP_{TH} =	Noise equivalent optical power due to thermal or amplifier noise
NEPID = NEP_{DC} =	Noise equivalent optical power due to photo-detector dark current
NEPSS = NEP_{SS} =	Noise equivalent optical power due to shot-noise generated by the signal
NEPSB = NEP_B =	Noise equivalent optical power due to shot-noise generated by the background

O

OMEGØ = ω_0 = Cloud particle single scaller albedo

OMEGR = Ω_R = Solid angle of the receiver

OMEGW = Ω_0 = Full solid angle containing the incoming in-water radiance

P

PR = $P_R(t)$ = Instantaneous received signal power

PRS = P_{SU} = Average optical power at receiver due to the sun

PRM = P_{MU} = Average optical power at receiver due to the moon

PRBS = P_{BS} = Average optical power at receiver due to the blue sky

PRZ = P_Z = Average optical power at receiver due to stellar and zodiacal light

PRBL = P_{BL} = Average optical power at receiver due to bioluminescence

PRPEAK = $\hat{P}_R$ = Peak received signal power

PHIHLF = $\phi_{1/2}$ = $\sqrt{f_a + f_{aw} + f_w}$

Q

Q = q = Parameter describing ability of satellite transmitter to correct for zenith

QE = e = Charge on electron

R

RANGE = R = Range from satellite to submarine

RL = R_L = Load resistance

RFLW = $R(\theta_S)$ = Sea surface reflectance

RESP = $(ne/h\nu)$ = Responsivity

RPS = f(t) = Received pulse shape

S

SCATØ = S =	Water scattering coefficient
SCATI or SCAT(I) = s_i =	Scattering coefficient of i'th water layer

T

THOPTA = b =	Effective clear atmosphere optical thickness
TABS =	Absolute temperature
THGC = T =	Geometrical thickness of the cloud
TI = t =	Time
TIPEAK = t_m =	Time after pulse start at which peak value occurs
TSGA = τ_a =	Signal clear atmospheric energy transmission
TSGC = τ_c =	Signal cloud energy transmission
THOPTC = τ_{OPT} =	Optical thickness of the cloud
TSGCW = τ_{cw} =	Signal cloud to water energy transmission
TSGAW = τ_{aw} =	Signal total energy transmission of air/water interface
TSGAWI = τ_{aw1} =	Signal air-water interface energy transmission due to the index of refraction discontinuity
TSGAWF = τ_{aw2} =	Signal air-water interface energy transmission due to foam and streaks on the sea surface
TSGW = τ_w =	Signal water energy transmission
TSBKA, TZBKA, TMBKA, TBSBKA = τ'_a =	Background clear atmospheric energy transmission
TSC = τ'_{CS} =	Cloud energy transmission of the direct sunlight
TMC = τ'_{CM} =	Cloud energy transmission of the direct moonlight
TBSC = τ_{CB} =	Cloud energy transmission of the blue skylight
TZC = τ'_{CZ} =	Cloud energy transmission of the stellar and zodiacal light
TBKCW = τ_{cw} =	Background cloud to water energy transmission

T (Continued)

TSAW
TMAW
TBSAW = τ_{AW} = Total background energy transmission of the air-water interface
TZAW

TBKAWF = τ_{AW2} = Background air/water interface transmission due to foam and streaks on the sea surface

TSAWN = τ_{AWIS} = Solar air/water interface transmission due to index of refraction discontinuity

TMAWN = τ_{AWIM} = Lunar air/water interface transmission due to index of refraction discontinuity

TBSAWN = τ_{AWIB} = Blue skylight air/water interface transmission due to index of refraction discontinuity

TZAWN = τ_{AWIZ} = Stellar and zodiacal light air/water interface transmission due to index of refraction discontinuity

TSW = τ_{WSU} = Solar water energy transmission

TMW = τ_{WMU} = Lunar water energy transmission

TBSW = τ_{WB} = Blue sky water energy transmission

TZW = τ_{WZ} = Stellar and zodiacal light water energy transmission

TABLE 1 - Table of τ_{awi} for THOPTC $\geq$ 10
TABLE 2 - Table of E_2

U

V

V = V = Surface wind speed

W

X

Y

Z

ZASGA = θ_S = Signal in-air zenith angle

ZASGW = θ_s^w = Signal in-water zenith angle

ZASA = θ_{SU} = Solar in-air zenith angle

ZAMA = θ_{MU} = Lunar in-air zenith angle

ZASW = θ_{su}^w = Solar in-water zenith angle

ZAMW = θ_{mu}^w = Lunar in-water zenith angle

4.4.3 Listing

TSD83.DSPDPR.FORT PAGE 0001
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```
      SUBROUTINE DSPDPR(THOPTA,THCZ,THOPTC,ATRUF,HC0,V,E,THW,J,ZASGA,
     $ADLTA,ZASA,ZAMA,ADLTAS,ADLTAM,ADLTAD,ADLTAZ,TSLUT,RANGE,IFIRST,
     $PAPEAK,NEPTOT)
      IMPLICIT REAL(A-Z)
      INTEGER I,J,NPH,NIM
      NAMELIST/INPUT/EI,GAMI,
     $COSACS,OMEGO,ACSCAT,NDEI,ANSWO,DEPR,ARFOV,
     $GAMO,DIAR,AS,LSE,AM,LMR,LDSE,LZE,SCATO,
     $BWOPT,AT,NOISPA,G,RESP,RL,ID,
     $NOISE,LBLR,RITOP2
C
      IF (IFIRST.EQ.0.0) GO TO 25
C     CHECK FOR FIRST PASS THROUGH SUBROUTINE: IF YES IFIRST=1.0
   10 READ(7,INPUT)
C     READ INPUT PARAMETERS INCLUDING UPDATES
C
      WRITE(6,INPUT)EI,GAMI,COSACS,OMEGO,ACSCAT,NDEI,ANSWO,DEPR,ARFOV,GAMO,
     $DIAR,AS,LSE,AM,LMR,LDSE,LZE,SCATO,BWOPT,AT,NOISPA,G,RESP,RL,ID,
     $NOISE,LBLR,RITOP2
   15 FORMAT(I10,E12.5)
   25 PI=2.0*ARCOS(0.0)
      DE=1.0E 19
      C=3.0E8
   30 TSGA=EXP(-THOPTA/COS(ZASGA*PI/180.))
C     CLEAR ATMOSPHERIC TRANSMISSION-SIGNAL
C     CALCULATION FOR OPTICAL THICKNESS OF CLOUD FOLLOWS.
C     PROGRAM WILL BRANCH TO HANDLE THICKNESS: THOPTC=0.,
C     0.LT.THOPTC.LT.10,AND THOPTC.GE.10.
C
   45 IF(THOPTC.LT.0.0) GO TO 9000
   50 IF(THOPTC-1.E-10) 2100,2100,51
   51 IF(THOPTC.GE.10.) GO TO 1100
C     **********
C     THIS SECTION WILL HANDLE CLOUD OPTICAL THICKNESS.GT.0.AND.LT.10.
C     ***** SIGNAL *****
C
C
      TEMP=(1.-.0050*THOPTC*1.69/(10.*(1.-COSACS)*1.42))
      TSGC=TEMP*(COS(ZASGA*PI/180.))**(Q*1.)
C     CLOUD SIGNAL ENERGY TRANSMISSION
  105 TSGCW=1.
C     CLOUD TO WATER ENERGY TRANSMISSION
C     THIS SECTION CALCULATES SIGNAL ENERGY TRANSMISSION OF AIR-WATER
C     INTERFACE.
  110 IF(V.LT.0.0.OR.V.GT.19.0) GO TO 9005
  112 IF(ZASGA.LT.0.0.OR.ZASGA.GT.90.0) GO TO 9010
  114 TSGAWO=DWLTAB(V,ZASGA)
C     INTERPOLATING ON TABLE FOR DOWNLINK.
  120 TSGAWP=1.-1.2E-5*V**3.5
  121 IF(V.GE.9.)TSGAWP=1.-(1.2E-5*V**3.5)*(1.2250*V-.991)
  125 TSGAW=TSGAWO*TSGAWP
C     SIGNAL ENERGY TRANSMISSION OF AIR-WATER INTERFACE
  130 SUM1=0.0
      DEPR=0.0
      SUM1=SUM1+KO*THW
  135 DEPR=DEPR+THW
      ZASW=ARSIN(SIN(ZASGA*PI/180.)/NW(K))
```

4.4.3 (Continued)

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```
140 TSGW=EXP(-SUMS/COS(ZASGW))                                          00000580
C     SIGNAL WATER ENERGY TRANSMISSION 130 140                          00000590
C                                                                       00000600
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF SIGNAL RADIANCE     00000610
150 FA=1.296*(TAU/NDEX)**2                                              00000620
152 FAW=.0101*.010+FA/(1.0*(180./PI))**2                                00000630
    TEMP2=ANSW*SCAT*DEPTH                                               00000640
154 FW=TEMP2/COS(ZASGW)                                                 00000650
156 ARDWQS=SQRT(FA+FAW*FW)                                              00000660
157 IF(ARDWQS.GT.50.2.OR.ARDWQS.LT.0.) GO TO 9015                       00000670
158 ARDWSG=INTERP(ARDWQS)                                               00000680
160 FSC=DSINDZ(ADELTA,ARDWSG,ARFOV)                                     00000690
C                                                                       00000700
C     THIS SECTION CALCULATES RECEIVED PULSE WIDTH AND SHAPE            00000710
C                                                                       00000720
170 DPWC=0.0                                                            00000730
C     PULSE WIDTH DUE TO WATER PORTION OF PATH                          00000740
172 DPWCW=2.*DEPTH*TAN(ARFOV*PI/180.)*SIN(ZASW*PI/180.)/C               00000750
C     ADDITIONAL PULSE WIDTH DUE TO CLOUD TO WATER PATH                 00000760
174 DPWW=((1./COS(ARFOV*PI/180.))/COS(ARFOV*PI/180.))*DEPTH*INDEX/C     00000770
C     PULSE WIDTH AFTER EMERGING FROM CLOUD                             00000780
180 TIPEAK=(DPWC+DPWCW+DPWW)/2.45                                       00000790
C                                                                       00000800
C     THIS SECTION CALCULATES TOTAL RECEIVED OPTICAL ENERGY PER PULSE   00000810
C                                                                       00000820
190 ER=(ET*GAMT/(PI*(ALT*ARFOV*PI/180.)**2./4.))*(PI*DIAREC*DIAR/4.)*   00000830
   &GAMR/(RANGE*RANGE))*TSGA*TSGC*TSGW*TSGC*TSGA*FSC                    00000840
C     TOTAL RECEIVED OPTICAL ENERGY PER PULSE                           00000850
C     PR=ER*T*EXP(-TT/TIPEAK)/TIPEAK**2.                                00000860
C     INSTANTANEOUS RECEIVED OPTICAL POWER                              00000870
195 PRPEAK=ER*EXP(-1.)/TIPEAK                                           00000880
C     PEAK INSTANTANEOUS RECEIVED OPTICAL POWER                         00000890
C                                                                       00000900
C     ******NOISE*****                                                  00000910
C                ***SOLAR***                                            00000920
200 IF(LSR.LE.0.0) GO TO 299                                            00000930
202 IF(ZASA.GT.90.0) GO TO 299                                          00000940
C                                                                       00000950
205 TSAA=EXP(-THDPTA/COS(ZASA*PI/180.))                                 00000960
C     BACKGROUND CLEAR ATMOSPHERE ENERGY TRANSMISSION                   00000970
207 TSC=TEMP*(COS(ZASA*PI/180.))**2                                     00000980
C     BACKGROUND CLOUD ENERGY TRANSMISSION                              00000990
209 TBACW=1.                                                            00001000
C     BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION                     00001010
C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR WATER    00001020
C     INTERFACE.                                                        00001030
215 TSAWN=BNEINE(V,ZASA)                                                00001040
C     INTERPOLATING ON TABLE FOR DOWNLINK.                              00001050
225 TSAW=TSGAW*TSAWN                                                    00001060
C     TOTAL BACKGROUND ENERGY TRANSMISSION IF AIR-WATER INTERFACE        00001070
    ZASW=ARSIN(SIN(ZASA*PI/180.)/NDEX)                                  00001080
230 TSW=EXP(-SUMS/COS(ZASW))                                            00001090
C     WATER ENERGY TRANSMISSION 230-240                                 00001100
250 LSR=LSR*TSA*TSC*TBACW*TSAW*TSW                                      00001110
C     AVERAGE BACKGROUND DUE TO SUNLIGHT                                00001120
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 260 270    00001130
260 FAS=FAS/NDEX**2.                                                    00001140
```

4.4.3 (Continued)

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262 FAUS=.01310+.0103*VV2./(1.+VV+1.E0./P1)**2                     00001150
264 FUSO=TEMP2/COS(ZASW)                                            00001160
266 ANMUSN=SQRT(FUSO+FAUS+FAS)                                      00001170
268 IF(ANMUN.GT.30.2.OR.ANMUN.LT.0.15) GO TO 2828                   00001180
270 ANMUS=INTERP(ANMUN)                                             00001190
280 PNS=OSTRO2(ADLTAS,ANMUS,ANFOV)                                  00001203
C     FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIE00001210
290 PBS=(SAVGAMM*(PI*DIAM)**2.*DMOPT*ENS)*(1.-COS(ANFOV*PI/180.))/2. 00001220
C     AVERAGE BACKGROUND POWER DUE TO SUNLIGHT                      00001233
295 GO TO 300                                                       00001240
299 PBS=0.0                                                         00001253
C     NO SOLAR CONTRIBUTION                                         00001263
C                 ***LUNAR***                                       00001270
300 IF(LVSA.LT.0.0) GO TO 399                                       00001283
302 IF(ZAMA.GT.90.0) GO TO 399                                      00001290
C                                                                   00001300
305 TAMA=EXP(-THOPTA/COS(ZAMA*PI/180.))                             00001316
C     BACKGROUND CLEAR ATMOSPHERE ENERGY TRANSMISSION               00001323
307 TAC=TEMP*(COS(ZAMA*PI/180.))**2                                 00001330
C     BACKGROUND CLOUD ENERGY TRANSMISSION                          00001340
309 TBCW=1.                                                         00001350
C     BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION                 00001360
C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR WATER 00001373
C     INTERFACE.                                                    00001380
315 TAWM=DNLINEV(ZAMA)                                              00001390
C     INTERPOLATING ON TABLE FOR DNUMBER.                           00001400
325 TAW=TAWM*SCAW                                                   00001413
C     TOTAL BACKGROUND ENERGY TRANSMISSION OF AIR WATER INTERFACE.  00001420
      ZAMW=ASIN(SIN(ZAMA*PI/180.)/NWATER)                           00001433
340 TWM=EXP(-SUM)/COS(ZAMW))                                        00001440
C     WATER ENERGY TRANSMISSION 330-340                             00001450
350 [illegible]                                                     00001463
C     AVERAGE BACKGROUND DUE TO MOONLIGHT                           00001473
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 360-370 00001483
360 FAM=(AM/WDR)**2.                                                00001490
362 FAUM=FAM                                                        00001503
364 FUMO=TEMP2/COS(ZAMW)                                            00001513
366 ANMUMN=SQRT(FUMO+FAUM+FAM)                                      00001523
368 IF(ANMUMN.GT.30.2.OR.ANMUMN.LT.0.1) GO TO 4029                  00001533
370 ANMUM=INTERP(ANMUMN)                                            00001543
380 FNM=OSTRO2(ADLTAM,ANMUM,ANFOV)                                  00001553
C     FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIE00001560
390 PBM=(AMOGAMM*(PI*DIAM)**2.*DMOPT*ENM)*(1.-COS(ANFOV*PI/180.))/2.  00001570
C     AVERAGE BACKGROUND POWER DUE TO MOONLIGHT                     00001580
395 GO TO 400                                                       00001590
399 PBM=0.0                                                         00001600
C     NO LUNAR CONTRIBUTION                                         00001610
C                 ***SKY***                                         00001620
400 IF(LDSA.LT.0.0) GO TO 499                                       00001633
401 IF(THOPTA.LT.0.2.OR.THOPTA.GT.0.6) GO TO 4040                   00001643
402 IF(ZASA.GE.90.0) GO TO 499                                      00001650
403 TOSKA=EXP(-THOPTA)                                              00001663
C     BACKGROUND CLEAR ATMOSPHERIC ENERGY TRANSMISSION              00001670
407 TOSC=.5*TEMP                                                    00001680
C     BACKGROUND CLOUD ENERGY TRANSMISSION                          00001690
409 TOSCW=1.                                                        00001700
C     BACKGROUND CLOUD TO WATER ENERGY [illegible]MISSION.          00001710
```

4.4.3 (Continued)

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C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR WATER
C     INTERFACE.
  415 TDSAWA=0.03
  425 TDSAW=TDSAWA*ISGAW
  440 TDSW=(1.0-SUMI)
C     WATER ENERGY TRANSMISSION 510-550
  450 [illegible]
C     AVERAGE BACKGROUND DUE TO BLUE SKY
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 560-570
  460 FABS=33.4002.
  462 FAWS=0.0
  464 FAWSO=TEMP2
  466 ARDWUN=SQRT(FAWSO*FAWS*FABS)
  469 IF(ARDWUN.GT.50.2.OR.ARDWUN.LT.0.0) GO TO 9010
  470 ARDWN=INTERP(ARDWUN)
  480 FHBS=DSIND/(ARD,ISD,ARDWNB,ARFOV)
C     FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW
  490 PBBS=[illegible]COSTAMF[illegible]/180.)**2.
C     AVERAGE BACKGROUND POWER DUE TO BLUE SKY
  495 GO TO 500
  499 PBBS=0.0
C     NO BLUE SKY CONTRIBUTION
C                 ***STELLAR/ZODIACAL LIGHT***
  500 IF(LZ.EQ.0.0) GO TO 557
  501 IF(THOPTA.LT.0.7.OR.THOPTA.GT.0.6) GO TO 9040
  505 TCMA=EZ(THOPTA)
C     BACKGROUND CLEAR ATMOSPHERIC ENERGY TRANSMISSION
  507 TCC=.5*TEMP
C     BACKGROUND CLOUD ENERGY TRANSMISSION
  509 TACW=1.
C     BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION
C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR-WATER
C     INTERFACE.
  515 TZAWA=0.03
  525 TZAW=TZAWA*ISGAW
  540 TZW=(1.0-SUMI)
C     WATER ENERGY TRANSMISSION 530 540
  550 [illegible]
C     AVERAGE BACKGROUND DUE TO STELLAR/ZODIACAL LIGHT
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 560-570
  560 FAZ=33.4002.
  562 FAWZ=0.0
  564 FWZO=TEMP2
  566 ARDWON=SQRT(FWZO*FAWZ*FAZ)
  569 IF(ARDWON.GT.50.2.OR.ARDWON.LT.0.0) GO TO 9015
  570 ARDWNZ=INTERP(ARDWON)
  580 FHZ=DSIND2(ARD,FAZ,ARDWNZ,ARFOV)
C     FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW
  590 PRZ=[illegible]COSTAMFOV[illegible]/180.)**2.
C     AVERAGE BACKGROUND POWER DUE TO STELLAR/ZODIACAL LIGHT
  595 GO TO 600
  599 PRZ=0.0
C     NO STELLAR/ZODIACAL LIGHT CONTRIBUTION
C                 ***BIOLUMINESCENCE***
  600 PBBL=[illegible]**2.)/4.
      GO TO 700
C     SUM OF THE AVERAGE BACKGROUND POWERS.
```

4.4.3 (Continued)

TSF03.DSPDPM.FORT PAGE 0005
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```
C
C
C      THIS SECTION WILL HANDLE CLOUD OPTICAL THICKNESS.GE.10.
C      ***** SIGNAL *****.
C
C
 1100 NUM3=1.69-0.5513*(ZASGA*PI/180.)+2.7173*((ASGA*PI/180.)**2-6.9066*
     1((ASGA*PI/180.)**3)+7.1446*((ASGA*PI/180.)**4-3.4249*((ASGA*PI/180.
     1)**5)+0.6159*((ASGA*PI/180.)**6
C
       TP3=1./((THOPTIC*(1.-COSACS)+1.42)*2.*SQRT(3.*(1.-COSACS)*(1.-
     2OMEGO))+(THOPTIC*1.42/(1.-COSACS))*(EXP(-(SQRT(3.*(1.-COSACS)*(1.-
     3OMEGO))*(THOPTIC*1.42/(1.-COSACS)))/(1.-(EXP(-2.*SQRT(3.*(1.-
     4COSACS)*(1.-OMEGO))*(THOPTIC*1.42/(1.-COSACS)))))
C
       TMP3=NUM3*TP3
       TSGC=TMP3*(COS((ASGA*PI/180.))**6
C      CLOUD SIGNAL ENERGY TRANSMISSION
 1105 TSGCW=1./((1.+(HCW/(RANGE*STAUF*PI/180./2.))**2.)
C      CLOUD TO WATER ENERGY TRANSMISSION
C      THIS SECTION CALCULATES SIGNAL ENERGY TRANSMISSION OF AIR-WATER
C      INTERFACE.
 1110 IF(V.LT.0.0.OR.V.GT.19.4) GO TO 9005
 1112 IF((ASGA.LT.0.0.OR.(ASGA.GT.90.0)) GO TO 9010
 1114 TSGAWD=0.03
C      INTERPOLATING ON TABLE FOR DOWNLINK.
 1120 TSGAWF=1.-(1.2E-5*V**3.)
 1121 IF(V.GE.9.)TSGAWF=1.-((1.2E-5*V**3.)*(1.+.2250*V-.99))
 1125 TSGAW=TSGAWD*TSGAWF
C      SIGNAL ENERGY TRANSMISSION OF AIR-WATER INTERFACE
 1130 SUM1=0.0
       DEPH=0.0
       SUM1=SUM1+K*TINC
 1135 DEPH=DEPH+TINC
 1140 TSGW=EXP(-SUM1)
C      SIGNAL WATER ENERGY TRANSMISSION 1130-1140
C
C      THIS SECTION CALCULATES WATER DISTRIBUTION OF SIGNAL RADIANCE
 1150 FA=33.0**2.
 1152 FAW=0.0
       TEMP2=ANSWO*SCAT0*DEPH
 1154 FW=TEMP2
 1156 ARDWQS=SQRT(FA*FAW*FW)
 1157 IF(ARDWQS.GT.50.2.OR.ARDWQS.LT.0.) GO TO 9015
 1158 ARDWSG=INTERP(ARDWQS)
 1160 PSG=DSIRO2(ARDTA,ARDWSG,ARFOV)
C
C      THIS SECTION CALCULATES RECEIVED PULSE WIDTH AND SHAPE
C
 1170 DPWC=THGC/C*(1.3/OMEGO/THOPTIC/((ACSCAT*PI/180.)**2)*((1.+2.25*OMEGO
     6*THOPTIC*((ACSCAT*PI/180.)**2))**1.5-1.)-1.)
C      PULSE WIDTH DUE TO WATER PORTION OF PATH
 1172 DPWCW=0.0
C      ADDITIONAL PULSE WIDTH DUE TO CLOUD TO WATER PATH
 1174 DPWW=((1.-COS(ARFOV*PI/180.))/COS(ARFOV*PI/180.))*DEPH*N*DEE/C
C      PULSE WIDTH AFTER EMERGING FROM CLOUD
 1180 TIPTAG=(DPWC+DPWW+...)**2.**5
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4.4.3 (Continued)


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C
C     THIS SECTION CALCULATES TOTAL RECEIVED OPTICAL ENERGY PER PULSE
C
 1190 ER=(E(0GAMT/(PI*(((AT0W*OPI/180.)**2.1/4.))*(((PI*D*(AR*PI/AR/4.)*(
     &GAMB/(RAVG+RANGE))))*TSCA*TSC*TSG*TSG*TSGAW*TSW
C     TOTAL RECEIVED OPTICAL ENERGY PER PULSE
C     PR=ER*(1*EXP(-1)/TIPEAK)/TIPEAK**2.
C     INSTANTANEOUS RECEIVED OPTICAL POWER
 1195 PRPEAK=ER*EXP(-1.)/TIPEAK
C     PEAK INSTANTANEOUS RECEIVED OPTICAL POWER
C
C     *****NOISE*****
C                     ***SOLAR***
 1200 IF(LSA.LE.0.0) GO TO 1299
 1202 IF(ZASA.GT.90.0) GO TO 1299
C
 1205 TSOHA=EXP(-THOPTA/COS(ZASA*PI/180.))
C     BACKGROUND CLEAR ATMOSPHERE ENERGY TRANSMISSION
      NUM3=1.69-0.5513*(ZASA*PI/180.)+2.7173*(ZASA*PI/180.)**2-6.9066*
     &(ZASA*PI/180.)**3+7.1556*(ZASA*PI/180.)**4-3.6249*(ZASA*PI/180.)
     &**5+0.6155*(ZASA*PI/180.)**6
      TMP3=NUM3*TP3
 1207 TSC=TMP3*(COS(ZASA*PI/180.))
C     BACKGROUND CLOUD ENERGY TRANSMISSION
 1209 TSRCW=1.
C     BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION
C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR WATER
C     INTERFACE.
 1225 TSAW=TSGAW
C     TOTAL BACKGROUND ENERGY TRANSMISSION IF AIR-WATER INTERFACE
 1240 TSW=TSGW
C     WATER ENERGY TRANSMISSION 1230-1240
 1250 LSW=LSA*TSOHA*TSC*TSRCW*TSAW*TSW
C     AVERAGE BACKGROUND DUE TO SUNLIGHT
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 1260 1270
 1260 FRS=FA
 1262 FAWS=0.0
 1264 FWSO=TEMP2
 1266 ARDWQW=ARDWQS
 1270 ARDWRS=ARDWSG
 1280 FNS=FSG
C     FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW
 1290 PRS=LSW*GAMR*(PI*DIAR)**2.*OMOPT*FNS*(1.-COS(ARFOV*PI/180.))/2.
C     AVERAGE BACKGROUND POWER DUE TO SUNLIGHT
 1295 GO TO 1300
 1299 PRS=0.0
C     NO SOLAR CONTRIBUTION
C                     ***LIMAR***
 1300 IF(LMR.LE.0.0) GO TO 1399
 1302 IF(ZAMA.GT.90.0) GO TO 1399
C
 1305 THOMA=EXP(-THOPTA/COS(ZAMA*PI/180.))
C     BACKGROUND CLEAR ATMOSPHERE ENERGY TRANSMISSION
      NUM3=1.69-0.5513*(ZAMA*PI/180.)+2.7173*(ZAMA*PI/180.)**2-6.9066*
     &(ZAMA*PI/180.)**3+7.1556*(ZAMA*PI/180.)**4-3.6249*(ZAMA*PI/180.
     &)**5+0.6155*(ZAMA*PI/180.)**6
      TMP3=NUM3*TP3
```

GTE SYLVANIA

4.4.3 (Continued)

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 1307 TBC=TBP3*(COS(ZANA*PI/180.))                                      00001430
C     BACKGROUND CLOUD ENERGY TRANSMISSION                              00001440
 1309 TBACW=1.                                                          00001450
C     BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION                     00001460
C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR WATER    00001470
C     INTERFACE.                                                        00001480
 1325 TBAW=TSGAW                                                        00001490
C     TOTAL BACKGROUND ENERGY TRANSMISSION OF AIR-WATER INTERFACE.      00001500
 1340 TBW=TSGW                                                          00001510
C     WATER ENERGY TRANSMISSION 1330 1350                               00001520
 1350 LBM=LMAO*TBMA*TBC*TBACW*TBAW*TBW                                  00001530
C     AVERAGE BACKGROUND DUE TO MOONLIGHT                               00001540
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 1360-1370  00001550
 1360 FAM=FA                                                            00001560
 1362 FAWM=0.0                                                          00001570
 1365 FWMO=TEMP2                                                        00001580
 1366 ARDWOM=ARDWOS                                                     00001590
 1370 ARDWAM=ARDWSG                                                     00001600
 1380 FMM=FSG                                                           00001610
C     FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIE 00001620
 1390 PMM=LMMO*GAMMO*(PI*DIAR)**2.*WOPT*FMM*(1.-COS(ARFOV*PI/180.))/2.  00001630
C     AVERAGE BACKGROUND POWER DUE TO MOONLIGHT                         00001640
 1395 GO TO 1400                                                        00001650
 1399 PMM=0.0                                                           00001660
C     NO LUNAR CONTRIBUTION                                             00001670
C                     ***BLUE SKY***                                    00001680
 1400 IF(LOSB.LE.0.0) GO TO 1499                                        00001690
 1401 IF(THOPTA.LT.0.7.OR.THOPTA.GT.0.6) GO TO 9050                     00001700
 1402 IF(ZASA.GE.90.0) GO TO 1499                                       00001710
 1405 TBSMA=E2(THOPTA)                                                  00001720
C     BACKGROUND CLEAR ATMOSPHERIC ENERGY TRANSMISSION                  00001730
 1407 TBSC=2.0*P(1.69/1.                                                00001740
C     BACKGROUND CLOUD ENERGY TRANSMISSION                              00001750
 1409 TBACW=1.                                                          00001760
C     BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION.                    00001770
C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR-WATER    00001780
C     INTERFACE.                                                        00001790
 1425 TBSAW=TSGAW                                                       00001800
 1440 TBSW=TSGW                                                         00001810
C     WATER ENERGY TRANSMISSION 1430-1440                               00001820
 1450 LBSM=LOSB*TBSMA*TBSC*TBACW*TBSAW*TBSW                             00001830
C     AVERAGE BACKGROUND DUE TO BLUE SKY                                00001840
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 1460-1470  00001850
 1460 FABS=FA                                                           00001860
 1462 FAWBS=0.0                                                         00001870
 1465 FWBSO=TEMP2                                                       00001880
 1466 ARDWBO=ARDWOS                                                     00001890
 1470 ARDWBD=ARDWSG                                                     00001900
 1480 FMBS=FSG                                                          00001910
C     FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIE 00001920
 1490 PMBS=LBSM*GAMMO*(PI*DIAR)**2*WOPT*FMBS*(1.-COS(ARFOV*PI/180.))/2. 00001930
C     AVERAGE BACKGROUND POWER DUE TO BLUE SKY                          00001940
 1495 GO TO 1500                                                        00001950
 1499 PMBS=0.0                                                          00001960
C     NO BLUE SKY CONTRIBUTION                                          00001970
C                     ***STELLAR/ZODIACAL LIGHT***                      00001980
 1500 IF(LLZ.LE.0.0) GO TO 1599                                         00001990
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4.4.3 (Continued)


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 1501 IF(THOPTA.LT.0.2.OR.THOPTA.GT.0.6) GO TO 9040              00004000
 1505 TZWA=TZ(THOPTA)                                             00004010
C      BACKGROUND CLEAR ATMOSPHERIC ENERGY TRANSMISSION           00004020
 1507 TZC=2.*(P3**1.69/).                                         00004030
C      BACKGROUND CLOUD ENERGY TRANSMISSION                       00004040
 1509 TBACW=1.                                                    00004050
C      BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION              00004060
C      THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION IF AIR-WATER 00004070
C      INTERFACE.                                                 00004080
 1522 TZAW=TSGAW                                                  00004090
 1540 TZW=TSGW                                                    00004100
C      WATER ENERGY TRANSMISSION 1530-1540                        00004110
 1550 TZR=TZA*TZAW*TZC*TBACW*TZAW*TZW                             00004120
C      AVERAGE BACKGROUND DUE TO STELLAR/ZODIACAL LIGHT           00004130
C      THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 1560-1570 00004140
 1560 FAZ=FA                                                      00004150
 1562 FAWZ=0.0                                                    00004160
 1564 FWZ0=TEMP2                                                  00004170
 1566 ARDWWZ=ARDWOS                                               00004180
 1580 FWZ=FSG                                                     00004190
C      FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW00004200
 1590 PBZ=(ZBO*ARRO*(PI*DIAR)**2*OMEGPT*FWZ*(1.-COS(ARFOV*PI/180.))/2.   00004210
C      AVERAGE BACKGROUND POWER DUE TO STELLAR/ZODIACAL LIGHT     00004220
 1595 GO TO 1600                                                  00004230
 1599 PBZ=0.0                                                     00004240
C      NO STELLAR/ZODIACAL LIGHT CONTRIBUTION                     00004250
C                   ****BIOLUMINESCENCE****                       00004260
 1600 PBBL=(LBL*OGAMM*PI*OMEGPT*(DIAR**2.))/4.                    00004270
      GO TO 700                                                   00004280
C      SUM OF THE AVERAGE BACKGROUND POWERS.                      00004290
C                                                                 00004300
C                                                                 00004310
C      THIS SECTION WILL HANDLE CLOUD OPTICAL THICKNESS.EQ.0.     00004320
C      ***** SIGNAL *****                                         00004330
C                                                                 00004340
C                                                                 00004350
 2100 TSGC=COS(ZASGA*PI/180.)**Q                                  00004360
C      CLOUD SIGNAL ENERGY TRANSMISSION                           00004370
 2105 TSGCW=1.                                                    00004380
C      CLOUD TO WATER ENERGY TRANSMISSION                         00004390
C      THIS SECTION CALCULATES SIGNAL ENERGY TRANSMISSION OF AIR-WATER 00004400
C      INTERFACE.                                                 00004410
 2110 IF(V.LT.0.0.OR.V.GT.19.6) GO TO 9005                        00004420
 2112 IF(ZASGA.LT.0.0.OR.ZASGA.GT.90.0) GO TO 9010                00004430
 2114 TSGAWN=DNLIN(V,ZASGA)                                       00004440
C      INTERPOLATING ON TABLE FOR DNLIN.                          00004450
 2120 TSGAWF=1.-1.2E-5*V**3.3                                     00004460
 2121 IF(V.GE.9.)TSGAWF=1.-(1.2E-5*V**3.3)*(.225*V-.99)           00004470
 2125 TSGAW=TSGAWN*TSGAWF                                         00004480
C      SIGNAL ENERGY TRANSMISSION OF AIR-WATER INTERFACE          00004490
 2130 SUM1=0.0                                                    00004500
      DEPR=0.0                                                    00004510
      SUM1=SUM1+AO*THW                                            00004520
 2135 DEPR=DEPR+THW                                               00004530
      ZASGW=ARSIN(SIN(ZASGA*PI/180.)/NDEX)                        00004540
 2140 TSGW=EXP(-SUM1/COS(ZASGW))                                  00004550
C      SIGNAL WATER ENERGY TRANSMISSION 2130-2160                 00004560
```

4.4.3 (Continued)


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C
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF SIGNAL RADIANCE
 2150 FA=1.296*ATOWF/NOE1)**2
 2152 FAW=.01039*.01039**2./(1.03*(180./PI))**2
      TEMP2=ANSW**SCAT)*DEPH
 2154 FW=TEMP2/COS(ZASGW)
 2156 ANDWQS=SQRT(FA+FAW+FW)
 2157 IF(ANDWQS.GT.50.2.OR.ANDWQS.LT.0.) GO TO 9015
 2158 ANDWSG=INTERP(ANDWQS)
 2160 ESG=DSIBB2(ADLIA,ANDWSG,ABEOVE)
C
C     THIS SECTION CALCULATES RECEIVED PULSE WIDTH AND SHAPE
C
 2170 DPWC=0.0
C     PULSE WIDTH DUE TO WATER PORTION OF PATH
 2172 DPWCW=2.*DEPR*TAN(AFOV*PI/180.)*SIN(ZASW*PI/180.)/C
C     ADDITIONAL PULSE WIDTH DUE TO CLOUD TO WATER PATH
 2175 DPWW=(1.-COS(AFOV*PI/180.))/COS(AFOV*PI/180.)*DEPROWDE/C
C     PULSE WIDTH AFTER EMERGING FROM CLOUD
 2180 TIPEAK=(DPWC+DPWCW+DPWW)/2.45
C
C     THIS SECTION CALCULATES TOTAL RECEIVED OPTICAL ENERGY PER PULSE
C
 2190 ER=(ET*GAMT/(PI*(ATOWF*PI/180.)**2./4.))*((PI*DIAR*DIAR/4.)*
     GAMR/(RANGE*RANGE))*TSCA*TSC*TSCW*TSA*TSW*SW*ES
C     TOTAL RECEIVED OPTICAL ENERGY PER PULSE
C     PR=ER*(EXP(-(T/TIPEAK))/TIPEAK**2.
C     INSTANTANEOUS RECEIVED OPTICAL POWER
 2195 PRPEAK=ER*EXP(-1.)/TIPEAK
C     PEAK INSTANTANEOUS RECEIVED OPTICAL POWER
C
C     *****NOISE*****
C                    ***SUNLAR***
 2202 IF(ZASA.GT.90.) GO TO 2299
C
 2205 TSMAA=EXP(-THDPTA/COS(ZASA*PI/180.))
C     BACKGROUND CLEAR ATMOSPHERE ENERGY TRANSMISSION
 2207 TSC=COS(ZASA*PI/180.)
C     BACKGROUND CLOUD ENERGY TRANSMISSION
 2209 TBKCW=1.
C     BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION
C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR WATER
C     INTERFACE.
 2215 TSAWN=FNLINE(V,ZASA)
C     INTERPOLATING ON TABLE FOR ROUNLINE.
 2229 TSAW=TSAWN*TSGAW
C     TOTAL BACKGROUND ENERGY TRANSMISSION OF AIR-WATER INTERFACE
      ZASW=ARSIN(SIN(ZASA*PI/180.)/NOE1)
 2240 TSW=EXP(-SUM/COS(ZASW))
C     WATER ENERGY TRANSMISSION 2230-2240
 2250 ESN=ESN*TSMA*TSC*TBKCW*TSAW*TSW
C     AVERAGE BACKGROUND DUE TO SUNLIGHT
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 2260-2270
 2260 FAS=(AS/NOE1)**2.
 2262 FAWS=FAW
 2264 FWSO=TEMP2/COS(ZASW)
 2266 ANDWQN=SQRT(FAS+FAWS+FWSO)
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4.4.3 (Continued)

ESD83.DSPOP4.FORT
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 2269 IF(ARDWON.GT.50.2.OR.ARDWON.LT.0.)GO TO 9020
 2270 ARDWNS=INTERP(ARDWON)
 2280 FNS=DSTRD2(ARLTAS,ARDWNS,ARFOV)
C     FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIE
 2290 PRS=LSR*GAMR*(PI*DIAR)**2.*RWOPT*FNS*(1.-COS(ARFOV*PI/180.))/2.
C     AVERAGE BACKGROUND POWER DUE TO SUNLIGHT
 2295 GO TO 2300
 2299 PRS=0.0
C     NO SOLAR CONTRIBUTION
C                     ***LUNAR***
 2300 IF(LMR.LE.0.0) GO TO 2399
 2302 IF(ZAMA.GT.90.0) GO TO 2399
C
 2305 TMOKA=EXP(-THOPTA/COS(ZAMA*PI/180.))
C     BACKGROUND CLEAR ATMOSPHERE ENERGY TRANSMISSION
 2307 TMC=COS(ZAMA*PI/180.)
C     BACKGROUND CLOUD ENERGY TRANSMISSION
 2309 TBKCW=1.
C     BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION
C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR WATER
C     INTERFACE.
 2315 TRAWN=DNLINK(V,ZAMA)
C     INTERPOLATING ON TABLE FOR DOWNLINK.
 2325 TMAW=TRAWN*ISCAW
C     TOTAL BACKGROUND ENERGY TRANSMISSION OF AIR-WATER INTERFACE.
      ZAMW=ARSIN(SIN(ZAMA*PI/180.)/NDEX)
 2340 TMW=EXP(-SUM1/COS(ZAMW))
C     WATER ENERGY TRANSMISSION 2330-2340
 2350 LMR=LMR*TMOKA*TMC*TBKCW*TMAW*TMW
C     AVERAGE BACKGROUND DUE TO MOONLIGHT
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 2360-2370
 2360 FAM=LAM/NDEX**2.
 2362 FAWM=FAM
 2364 FWMO=TEMP2/COS(ZAMW)
 2366 ARDWON=SQRT(FWMO*FAWM*FAM)
 2369 IF(ARDWON.GT.50.2.OR.ARDWON.LT.0.) GO TO 9025
 2370 ARDWNM=INTERP(ARDWON)
 2380 FNM=DSTRD2(ARLTAM,ARDWNM,ARFOV)
C     FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIE
 2390 PRM=LMR*GAMR*(PI*DIAR)**2.*RWOPT*FNM*(1.-COS(ARFOV*PI/180.))/2.
C     AVERAGE BACKGROUND POWER DUE TO MOONLIGHT
 2395 GO TO 2400
 2399 PRM=0.0
C     NO LUNAR CONTRIBUTION
C                     ***BLUE SKY***
 2400 IF(LBSK.LE.0.0) GO TO 2499
 2401 IF(THOPTA.LT.0.2.OR.THOPTA.GT.0.6) GO TO 9040
 2402 IF(ZASA.GE.90.0) GO TO 2499
 2405 TBSMKA=E2(THOPTA)
C     BACKGROUND CLEAR ATMOSPHERIC ENERGY TRANSMISSION
 2407 TBSC=1.
C     BACKGROUND CLOUD ENERGY TRANSMISSION
 2409 TBKCW=1.
C     BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION.
C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR-WATER
C     INTERFACE.
 2415 TBSAWN=0.0)
```

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WESTERN DIVISION

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 2625 TBSAW=TBSAW*TSGAWP                                                  00005710
 2640 TBSW=EXP(-SUMI)                                                     00005720
C      WATER ENERGY TRANSMISSION 2630-2660                                00005730
 2650 LBSA=LBSA*TBSDA*TBSC*TBAC*TBSAW*TBSW                                00005752
C      AVERAGE BACKGROUND DUE TO BLUE SKY                                 00005753
C      THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 2660-2670   00005760
 2660 FABS=33.8**2.                                                       00005770
 2662 FAWBS=0.0                                                           00005780
 2664 FWBSO=TEMP2                                                         00005790
 2666 ARDWON=SQRT(FWBSO+FAWBS+FABS)                                       00005800
 2669 IF(ARDWON.GT.50.2.OR.ARDWON.LT.0.0) GO TO 9030                      00005810
 2670 ARDWNB=INTERP(ARDWON)                                               00005820
 2680 FNBS=DSTRD2(ADLTAB,ARDWNB,ARFOV)                                    00005830
C      FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW00005843
 2690 PRBS=LBSA*GAMR*(PI*DIAR)**2*RWOPT*FNBS*(1.-COS(ARFOV*PI/180.))/2. 00005853
C      AVERAGE BACKGROUND POWER DUE TO BLUE SKY                           00005860
 2695 GO TO 2500                                                          00005870
 2699 PRBS=0.0                                                             00005880
C      NO BLUE SKY CONTRIBUTION                                           00005890
C                    ***STELLAR/ZODIACAL LIGHT***                         00005900
 2500 IF(LZ.LE.0.0) GO TO 2599                                            00005910
 2501 IF(INOPT(3.LT.0.2.OR.INOPT(3.GT.0.4)) GO TO 9040                    00005920
 2505 TZBCA=T2(INOPT(A)                                                   00005935
C      BACKGROUND CLEAR ATMOSPHERIC ENERGY TRANSMISSION                    00005943
 2507 TZC=1.                                                               00005950
C      BACKGROUND CLOUD ENERGY TRANSMISSION                               00005960
 2509 TBACW=1.                                                             00005973
C      BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION                       00005980
C      THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION IF AIR-WATER     00005995
C      INTERFACE.                                                         00006000
 2515 TZAWN=0.83                                                          00006010
 2525 TZAW=TZAWN*TSGAWP                                                   00006020
 2540 TZW=EXP(-SUMI)                                                      00006030
C      WATER ENERGY TRANSMISSION 2530-2550                                00006040
 2550 LZR=LZ*TZBCA*TZC*TBACW*TZAW*TZW                                     00006053
C      AVERAGE BACKGROUND DUE TO STELLAR/ZODIACAL LIGHT                   00006060
C      THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 2560-2570   00006073
 2560 FAZ=33.8**2.                                                        00006080
 2562 FAWZ=0.0                                                            00006090
 2565 FWZO=TEMP2                                                          00006100
 2566 ARDWON=SQRT(FWZO+FAWZ+FAZ)                                          00006110
 2569 IF(ARDWON.GT.50.2.OR.ARDWON.LT.0.0) GO TO 9035                      00006120
 2570 ARDWNZ=INTERP(ARDWON)                                               00006133
 2580 FNZ=DSTRD2(ADLTAZ,ARDWNZ,ARFOV)                                     00006140
C      FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW00006150
 2590 PRZ=LZR*GAMR*(PI*DIAR)**2.*RWOPT*FNZ*(1.-COS(ARFOV*PI/180.))/2.     00006160
C      AVERAGE BACKGROUND POWER DUE TO STELLAR/ZODIACAL LIGHT             00006173
 2595 GO TO 2600                                                          00006180
 2599 PRZ=0.0                                                             00006190
C      NO STELLAR/ZODIACAL LIGHT CONTRIBUTION                             00006200
C                    ***BIOLUMINESCENCE***                                00006210
 2600 PRBL=(LBL*R*GAMR*PI*RWOPT*(DIAR**2.))/4.                            00006223
C      CALCULATIONS FOR ALL THOPTIC CONVERGE HERE.                        00006230
  700 PRTOT=PRS+PRM+PRBS+PRZ+PRBL                                         00006240
C      SUM OF THE AVERAGE BACKGROUND POWERS.                              00006253
  800 BWE=3.5/(2.*5*T(PEAK)                                               00006260
C      ELECTRICAL DETECTION BANDWIDTH                                     00006270
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```
C
  850 IF(2.95*TPEAK-TSLOT)910,910,860
  860 WRITE(6,861)
  861 FORMAT(1X,10('*'),'LASER PULSE WIDTH IS GREATER THAN SLOT WIDTH FO
     1R COORDINATES GIVEN ON FOLLOWING LINE',10('*'))
C
C
C
C     THIS SECTION CALCULATES TOTAL NOISE EQUIVALENT (OPTICAL) POWER DUE
C     TO ALL SOURCES.
C
  910 NEPSB=SQRT(2.*QE*B*E*NOISF*PATOT)/RESP)
C     NOISE EQ. OPTICAL POWER DUE TO SHOT NOISE GENERATED BY BACKGROUND.
C
  920 NEPTH=SQRT(4.*KT*BW*NOISFA/(RL*(G*RESP)**2.))
C     NOISE EQ. OPTICAL POWER DUE TO THERMAL OR AMPLIFIER NOISE.
C
  930 NEPID=SQRT(2.*QE*BW*NOISF*ID/RESP)
C     NOISE EQ. OPTICAL POWER DUE TO PHOTO-DETECTOR DARK CURRENT.
C
  940 NEPSS=SQRT(2.*QE*BW*NOISF*PRPEAK/RESP)
C     NOISE EQ. OPTICAL POWER DUE TO SHOT NOISE GENERATED BY SIGNAL.
C
  950 NEPTOT=SQRT(NEPTH**2.+NEPID**2.+NEPSS**2.+NEPSB**2.)
C     TOTAL NOISE EQUIVALENT OPTICAL POWER DUE TO ALL SOURCES.
C
  960 IF(NSTOP2.EQ.0.0)GO TO 9999
C     NSTOP2 DETERMINES WHETHER TO PRINT INTERMEDIATE CALCULATIONS
C     ***********OUTPUT*************
C
      WRITE(6,0002)
 0002 FORMAT(///30X,'OUTPUT FOR SIGNAL SECTION'//)
      WRITE(6,0030)TSGA
 0030 FORMAT(1X,E12.5,5X,'TSGA',12X,'CLEAR ATMOSPHERIC TRANS')
      WRITE(6,0040) THOPTC
 0040 FORMAT(1X,E12.5,5X,'THOPTC',10X,'OPTICAL THICKNESS OF CLOUD')
      WRITE(6,0100) TSGC
 0100 FORMAT(1X,E12.5,5X,'TSGC',12X,'CLOUD ENERGY TRANS.')
      WRITE(6,0105) TSGCW
 0105 FORMAT(1X,E12.5,5X,'TSGCW',11X,'CLOUD-WATER ENERGY TRANS.')
      WRITE(6,0125) TSGAW
 0125 FORMAT(1X,E12.5,5X,'TSGAW',11X,'AIR-WATER INTERFACE TRANS.')
      WRITE(6,0140) TSGW
 0140 FORMAT(1X,E12.5,5X,'TSGW',12X,'WATER ENERGY TRANS.')
      WRITE(6,0150) FA
 0150 FORMAT(1X,E12.5,5X,'FA',14X,'ATMOS. CONT. TO RECVD BEAM HF-ANGLE')
      WRITE(6,0152) FAW
 0152 FORMAT(1X,E12.5,5X,'FAW',13X,'AIR-WATER CONT TO RCVD BM HF-ANGLE')
      WRITE(6,0154) FW
 0154 FORMAT(1X,E12.5,5X,'FW',14X,'WATER CONT TO RCVD BEAM HF-ANGLE')
      WRITE(6,0158) ARDWSG
 0158 FORMAT(1X,E12.5,5X,'ARDWSG',10X,'IN WATER RADIANCE HF-ANGLE')
      WRITE(6,0160) FSG
 0160 FORMAT(1X,E12.5,5X,'FSG',13X,'WATER DIST OF RADIANCE')
      WRITE(6,0170) DPWC
 0170 FORMAT(1X,E12.5,5X,'DPWC',12X,'DELTA PULSE WIDTH-CLOUDS')
      WRITE(6,0172) DPWCW
```

4.4.3 (Continued)


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0172 FORMAT(1X,E12.5,5X,'DPWCW',11X,'DELTA PULSE WIDTH-CLOUD TO WATER')
     WRITE(6,0175) DPWW
0175 FORMAT(1X,E12.5,5X,'DPWW',12X,'DELTA PULSE WIDTH-WATER')
     WRITE(6,0180) TIPEAK
0180 FORMAT(1X,E12.5,5X,'TIPEAK',10X,'TIME OF PEAK VALUE OF PULSE')
     WRITE(6,0190) ER
0190 FORMAT(1X,E12.5,5X,'ER',14X,'TOTAL RECEIVED ENERGY PER PULSE')
     WRITE(6,0195)PPPEAK
0195 FORMAT(1X,E12.5,5X,'PPPEAK',10X,'PEAK INSTANT RECVD POWER')
     WRITE(6,0200)
0200 FORMAT(///30X,'OUTPUT FOR NOISE SECTION'//)
     WRITE(6,0201) THOPTC
0201 FORMAT(1X,E12.5,5X,'THOPTC',10X,'OPTICAL THICKNESS OF CLOUD')
0202 WRITE(6,0203)
0203 FORMAT(/40X,'SOLAR CONTRIBUTION'/)
     IF(PPS.LE.0.0) GO TO 0299
0204 WRITE(6,0205) TSAAA
0205 FORMAT(1X,E12.5,5X,'TSAAA',11X,'CLEAR ATMOSPHERIC TRANS.')
     WRITE(6,0207) TSC
0207 FORMAT(1X,E12.5,5X,'TSC',13X,'CLOUD ENERGY TRANS.')
     WRITE(6,0209) TARCW
0209 FORMAT(1X,E12.5,5X,'TARCW',11X,'CLOUD TO WATER ENERGY TRANS.')
     WRITE(6,0225) TSAW
0225 FORMAT(1X,E12.5,5X,'TSAW',12X,'ENERGY TRANS,AIR-WATER INTERFACE')
     WRITE(6,0240) TSW
0240 FORMAT(1X,E12.5,5X,'TSW',13X,'WATER ENERGY TRANS.')
     WRITE(6,0250) LSR
0250 FORMAT(1X,E12.5,5X,'LSR',13X,'SPECTRAL RAD. AT RCVR APERTURE')
     WRITE(6,0260) PAS
0260 FORMAT(1X,E12.5,5X,'PAS',13X,'ATMOS. CONT TO RCVD BM HF-ANGLE')
     WRITE(6,0262) PAWS
0262 FORMAT(1X,E12.5,5X,'PAWS',12X,'AIR-WATER CONT TO RCVD BM HF ANGLE')
     WRITE(6,0265) PWSO
0265 FORMAT(1X,E12.5,5X,'PWSO',12X,'WATER CONT TO RCVD BM HF-ANGLE')
     WRITE(6,0270) ARDWNS
0270 FORMAT(1X,E12.5,5X,'ARDWNS',10X,'IN-WATER RADIANCE HF-ANGLE')
     WRITE(6,0280) FNS
0280 FORMAT(1X,E12.5,5X,'FNS',13X,'FRAC INC RAD IN RCVR FLD OF VIEW')
     WRITE(6,0290) PNS
0290 FORMAT(1X,E12.5,5X,'PNS',13X,'AVERAGE BACKGROUND POWER')
     GO TO 0302
0298 WRITE(6,0299) PNS
0299 FORMAT(/1X,E12.5,5X,'PNS',13X,'***** NO SOLAR CONTRIBUTION'/)
0302 WRITE(6,0303)
0303 FORMAT(/40X,'LUNAR CONTRIBUTION'/)
     IF(PPM.LE.0.0) GO TO 0390
0304 WRITE(6,0305) TMAAA
0305 FORMAT(1X,E12.5,5X,'TMAAA',11X,'CLEAR ATMOSPHERIC TRANS.')
     WRITE(6,0307) TMC
0307 FORMAT(1X,E12.5,5X,'TMC',13X,'CLOUD ENERGY TRANS.')
     WRITE(6,0309) TMRCW
0309 FORMAT(1X,E12.5,5X,'TMRCW',11X,'CLOUD TO WATER ENERGY TRANS.')
     WRITE(6,0325) TMAW
0325 FORMAT(1X,E12.5,5X,'TMAW',12X,'ENERGY TRANS,AIR-WATER INTERFACE')
     WRITE(6,0340) TMW
0340 FORMAT(1X,E12.5,5X,'TMW',13X,'WATER ENERGY TRANS.')
     WRITE(6,0350) LMR
```

4.4.3 (Continued)

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0350 FORMAT(1X,E12.5,5X,'LRN',13X,'SPECTRAL RAD. AT RCVR APERTURE')
     WRITE(6,0360) FAN
0360 FORMAT(1X,E12.5,5X,'FAN',13X,'ATMOS. CONT TO RCVR ON NF-ANGLE')
     WRITE(6,0362) FAWN
0362 FORMAT(1X,E12.5,5X,'FAWN',12X,'AIR WATER CONT TO RCVR ON NF-ANGLE')
     WRITE(6,0364) FWNO
0364 FORMAT(1X,E12.5,5X,'FWNO',12X,'WATER CONT TO RCVR ON NF-ANGLE')
     WRITE(6,0370) ARDWNN
0370 FORMAT(1X,E12.5,5X,'ARDWNN',10X,'IN WATER RADIANCE NF-ANGLE')
     WRITE(6,0380) FNN
0380 FORMAT(1X,E12.5,5X,'FNN',13X,'FRAC INC RAD IN RCVR FLD OF VIEW')
     WRITE(6,0390) PRN
0390 FORMAT(1X,E12.5,5X,'PRN',13X,'AVERAGE BACKGROUND POWER')
     GO TO 0402
0398 WRITE(6,0399) PRN
0399 FORMAT(/1X,E12.5,5X,'PRN',13X,'***** NO LUNAR CONTRIBUTION'/)
0402 WRITE(6,0403)
0403 FORMAT(/40X,'BLUE SKY CONTRIBUTION'/)
     IF(PRBS.LE.0.0) GO TO 0498
0404 WRITE(6,0405) TBSMA
0405 FORMAT(1X,E12.5,5X,'TBSMA',10X,'CLEAR ATMOSPHERIC TRANS.')
     WRITE(6,0407) TBSC
0407 FORMAT(1X,E12.5,5X,'TBSC',12X,'CLOUD ENERGY TRANS.')
     WRITE(6,0409) TBSCW
0409 FORMAT(1X,E12.5,5X,'TBSCW',11X,'CLOUD TO WATER ENERGY TRANS.')
     WRITE(6,0425) TBSAW
0425 FORMAT(1X,E12.5,5X,'TBSAW',11X,'ENERGY TRANS.AIR-WATER INTERFACE')
     WRITE(6,0440) TBSW
0440 FORMAT(1X,E12.5,5X,'TBSW',12X,'WATER ENERGY TRANS.')
     WRITE(6,0450) LBSN
0450 FORMAT(1X,E12.5,5X,'LBSN',12X,'SPECTRAL RAD. AT RCVR APERTURE')
     WRITE(6,0460) FABS
0460 FORMAT(1X,E12.5,5X,'FABS',12X,'ATMOS. CONT TO RCVR ON NF-ANGLE')
     WRITE(6,0462) FAWBS
0462 FORMAT(1X,E12.5,5X,'FAWBS',11X,'AIR-WATR CONT TO RCVR ON NF-ANGLE')
     WRITE(6,0464) FWBSO
0464 FORMAT(1X,E12.5,5X,'FWBSO',11X,'WATER CONT TO RCVR ON NF-ANGLE')
     WRITE(6,0470) ARDWNB
0470 FORMAT(1X,E12.5,5X,'ARDWNB',10X,'IN-WATER RADIANCE NF-ANGLE')
     WRITE(6,0480) FNBS
0480 FORMAT(1X,E12.5,5X,'FNBS',12X,'FRAC INC RAD IN RCVR FLD OF VIEW')
     WRITE(6,0490) PRBS
0490 FORMAT(1X,E12.5,5X,'PRBS',12X,'AVERAGE BACKGROUND POWER')
     GO TO 0502
0498 WRITE(6,0499) PRBS
0499 FORMAT(/1X,E12.5,5X,'PRBS',12X,'***** NO BLUE SKY CONTRIBUTION'/)
0502 WRITE(6,0503)
0503 FORMAT(/40X,'STELLAR-ZODIACAL CONTRIBUTION'/)
     IF(PRZ.LE.0.0) GO TO 0598
0504 WRITE(6,0505) TZMA
0505 FORMAT(1X,E12.5,5X,'TZMA',11X,'CLEAR ATMOSPHERIC TRANS.')
     WRITE(6,0507) TZC
0507 FORMAT(1X,E12.5,5X,'TZC',13X,'CLOUD ENERGY TRANS.')
     WRITE(6,0509) TZCW
0509 FORMAT(1X,E12.5,5X,'TZCW',11X,'CLOUD TO WATER ENERGY TRANS.')
     WRITE(6,0525) TZAW
0525 FORMAT(1X,E12.5,5X,'TZAW',12X,'ENERGY TRANS,AIR WATER INTERFACE')
```

4.4.3 (Continued)


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      WRITE(6,0540) EZA
0540  FORMAT(1H,E12.5,5X,'EZA',11X,'WATER ENERGY TRANS.')
      WRITE(6,0550) EZP
0550  FORMAT(1H,E12.5,5X,'EZP',11X,'SPECTRAL RES. AT BLUE GREEN')
      WRITE(6,0560) PAZ
0560  FORMAT(1H,E12.5,5X,'PAZ',11X,'ATMOS. CONT TO ACVD BR AT ANGLE')
      WRITE(6,0562) PAWC
0562  FORMAT(1H,E12.5,5X,'PAWC',12X,'AIR WATER CONT TO ACVD BR AT ANGLE')
      WRITE(6,0565) PAZW
0565  FORMAT(1H,E12.5,5X,'PAZW',12X,'WATER CONT TO ACVD BR AT ANGLE')
      WRITE(6,0570) [illegible]
0570  FORMAT(1H,E12.5,5X,'[illegible]',12X,'IN WATER RADIANCE AT ANGLE')
      WRITE(6,0580) PNF
0580  FORMAT(1H,E12.5,5X,'PNF',11X,'FRAC INC RAD IN ACVD FLD OF VIEW')
      WRITE(6,0590) PBF
0590  FORMAT(1H,E12.5,5X,'PBG',11X,'AVERAGE BACKGROUND POWER')
      GO TO 0595
0592  WRITE(6,0594) PBF
0594  FORMAT(/1H,E12.5,5X,'PBF',11X,'***** NO SIG- (NO CONTRIBUTION)')
0595  WRITE(6,0600)[illegible]
0600  FORMAT(/60X,'[illegible]'//1H,E12.5,5X,'PBBL',12X,'AVERAGE BAC
     KGROUND POWER')
      WRITE(6,0700)PBTOT
0700  FORMAT(//1H,E12.5,5X,'PBTOT',11X'SUM OF AVERAGE BACKGND POWERS')
      WRITE(6,0800)NEP
0800  FORMAT(/,/1H,E12.5,5X,'NEP',11X,'ELECTRICAL DETECTION BANDWIDTH')
      WRITE(6,0900)
0900  FORMAT(/60X,'NOISE EQUIVALENT OPTICAL POWERS'/)
      WRITE(6,0910)NEPSB
0910  FORMAT(1H,E12.5,5X,'NEPSB',11X,'PWR SHOT NOISE GEN. BY BACKGND')
      WRITE(6,0920)NEPTH
0920  FORMAT(1H,E12.5,5X,'NEPTH',11X,'PWR THERMAL OR AMPLIFIER NOISE')
      WRITE(6,0930)NEPID
0930  FORMAT(1H,E12.5,5X,'NEPID',11X,'PWR PHOTO DETECTOR DARK CURRENT')
      WRITE(6,0940)NEPSS
0940  FORMAT(1H,E12.5,5X,'NEPSS',11X,'PWR SHOT NOISE GEN. BY SIGNAL')
      WRITE(6,0950)NEPTOT
0950  FORMAT(1H,E12.5,5X,'NEPTOT',12X,'NOISE EQ. POWER-ALL SOURCES')
      GO TO 9999
C     ERROR MESSAGES
9000  WRITE(6,9001)
9001  FORMAT(1X,'ERROR.  [illegible] IS NEGATIVE')
      GO TO 9999
9005  WRITE(6,9006)
9006  FORMAT(1X,'ERROR. V IS NOT WITHIN LIMITS FOR LOOKUP TABLE')
      GO TO 9999
9010  WRITE(6,9011)
9011  FORMAT(1X,'ERROR. ZASCA IS NOT WITHIN LIMITS FOR LOOKUP TABLE')
      GO TO 9999
9015  WRITE(6,9016)
9016  FORMAT(1X,'ERROR. [illegible] IS NOT WITHIN LIMITS FOR LOOKUP TABLE')
      GO TO 9999
9020  WRITE(6,9021)
9021  FORMAT(1X,'ERROR. [illegible] NOT IN LIMITS FOR LOOKUP TABLE')
      GO TO 9999
9025  WRITE(6,9026)
9026  FORMAT(1X,'ERROR. [illegible] NOT IN LIMITS FOR LOOKUP TABLE')
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4.4.3 (Continued)

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      GO TO 9999
 9030 WRITE(6,9031)
 9031 FORMAT(1X,'ERROR. ARGMON DSKY NOT IN LIMITS FOR LOOKUP TABLE')
      GO TO 9999
 9035 WRITE(6,9036)
 9036 FORMAT(1X,'ERROR. ARGMON SIGMA NOT IN LIMITS FOR LOOKUP TABLE')
      GO TO 9999
 9040 WRITE(6,9041)
 9041 FORMAT(1X,'ERROR. THETA NOT IN LIMITS FOR LOOKUP TABLE.')
 9999 RETURN
      END
 3000 REAL FUNCTION INTERP(X)
      IMPLICIT REAL(A-Z)
      INTEGER I,J,MPH,MTH
C     LINEAR INTERPOLATION TO DETERMINE WATER DISTRIBUTION OF RADIANCE
C
      DIMENSION PHIMLF(20),PHI0(20)
      DATA PHIMLF/0.0,3.8,7.6,11.4,15.2,19.0,22.7,26.5,30.2,33.9,
     $37.5,41.1,44.6,48.1,51.6,54.9,58.2/,PHI0/0.0,5.0,10.0,15.0,
     $20.0,25.0,30.0,35.0,40.0,45.0,50.0,55.0,60.0,65.0,70.0,
     $75.0,80.0,85.0,90.0/
C
C     FIND ANGULAR INTERVAL
      J=0
 3010 J=J+1
      IF(X-PHIMLF(J)) 3020,3100,3010
C     INTERPOLATION FOLLOWS
 3020 INTERP=(X-PHIMLF(J-1))/(PHIMLF(J)-PHIMLF(J-1))*5.+PHI0(J-1)
      RETURN
C     NO INTERPOLATION NECESSARY
 3100 INTERP=PHI0(J)
      RETURN
      END
C
C
 5000 REAL FUNCTION BRLINK(V,FAS)
      IMPLICIT REAL(A-Z)
      INTEGER I,J,MPH,MTH
      DIMENSION TABLE(20,10)
C     ***WIND SPEED (V) IN METERS/SECOND***
      DATA TABLE/7-1.,8.,5.,10.,15.,20.,25.,30.,35.,40.,45.,
     $50.,55.,60.,65.,70.,75.,80.,85.,90.,0.0,.979,.975,
     $.964,.965,.920,.887,.847,.808,.767,.687,.620,.548,
     $.969,.305,.295,.283,.113,.0361,.0,1.03,.977,.974,
     $.962,.966,.918,.885,.845,.798,.765,.685,.619,.546,
     $.966,.305,.298,.209,.176,.0618,.0765,2.06,.976,.972,
     $.961,.963,.917,.886,.844,.797,.763,.686,.617,.545,
     $.968,.305,.299,.214,.136,.0751,.0190,4.12,.974,.970,
     $.959,.963,.914,.881,.841,.794,.761,.681,.615,.541,
     $.966,.306,.303,.224,.153,.0969,.0594,7.21,.973,.964,
     $.955,.936,.910,.877,.837,.790,.736,.677,.611,.540,.465,
     $.307,.313,.234,.172,.119,.0809,10.3,.967,.961,.951,.933,.907,.873,
     $.833,.786,.733,.673,.604,.536,.464,.389,.315,.247,.186,.135,.0961,
     $13.4,.961,.950,.940,.929,.903,.870,.829,.782,.729,.669,.605,.536,
     $.464,.391,.321,.255,.197,.150,.100,16.5,.960,.956,.944,.926,.899,
     $.866,.826,.779,.725,.666,.602,.534,.464,.393,.375,.262,.206,.157,
     $.117,19.6,.956,.952,.941,.922,.895,.861,.822,.775,.722,.661,.599,
```

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```
      0.512,.461,.395,.329,.260,.211,.165,.126/                            00009130
C     FUNCTION WILL INTERPOLATE TO FIND TIME-AVERAGED DOWNLINK AIR-SEA     00009140
C     INTERFACE TRANSMITTANCE FOR THOPIC.GT.0 AND THOPIC.LT.13             00009150
C                                                                          00009160
C     FIND WIND SPEED INTERVAL                                             00009170
      J=0                                                                  00009180
 5010 J=J+1                                                                00009190
C                                                                          00009200
      IF(V-TABLE(1,J)) 5020,5020,5010                                      00009210
C     FIND SIGNAL ZENITH ANGLE INTERVAL                                    00009220
 5020 I=0                                                                  00009230
 5030 I=I+1                                                                00009240
      IF(ZAS-TABLE(I,1)) 5040,5050,5030                                    00009250
C                                                                          00009260
C     FOLLOWING CHECKS TO SEE WHAT TYPE OF INTERPOLATION IS NECESSARY      00009270
C                                                                          00009280
 5040 IF(V.EQ.TABLE(1,J).AND.ZAS.EQ.TABLE(I,1))  GO TO 5060                00009290
 5042 IF(V.NE.TABLE(1,J).AND.ZAS.EQ.TABLE(I,1)) GO TO 5070                 00009300
 5044 IF(V.EQ.TABLE(1,J).AND.ZAS.NE.TABLE(I,1)) GO TO 5080                 00009310
C                                                                          00009320
C     INTERPOLATION FOLLOWS                                                00009330
C                                                                          00009340
 5050 DWLINK=((TABLE(I,1)-ZAS)*(TABLE(1,J)-V)*TABLE(I-1,J-1)+              00009350
     2(TABLE(I,1)-ZAS)*(V-TABLE(1,J-1))*TABLE(I-1,J)+                      00009360
     3(ZAS-TABLE(I-1,1))*(TABLE(1,J)-V)*TABLE(I,J-1)+                      00009370
     4(ZAS-TABLE(I-1,1))*(V-TABLE(1,J-1))*TABLE(I,J))/                     00009380
     5(TABLE(1,J)-TABLE(1,J-1))/(TABLE(I,1)-TABLE(I-1,1))                  00009390
C                                                                          00009400
C     INTERPOLATION FOR BOTH PARAMETERS                                    00009410
C                                                                          00009420
      RETURN                                                               00009430
C                                                                          00009440
 5060 DWLINK=TABLE(I,J)                                                    00009450
C                                                                          00009460
C     NO INTERPOLATION NECESSARY                                           00009470
      RETURN                                                               00009480
 5070 DWLINK=TABLE(I,J-1)+(V-TABLE(1,J-1))/(TABLE(1,J)-TABLE(1,            00009490
     1J-1))*(TABLE(I,J)-TABLE(I,J-1))                                      00009500
C                                                                          00009510
C     INTERPOLATION FOR WIND SPEED ONLY                                    00009520
      RETURN                                                               00009530
C                                                                          00009540
 5080 DWLINK=TABLE(I-1,J)+(ZAS-TABLE(I-1,1))/(TABLE(I,1)-                  00009550
     1TABLE(I-1,1))*(TABLE(I,J)-TABLE(I-1,J))                              00009560
C                                                                          00009570
C     INTERPOLATION FOR ZENITH ANGLE ONLY                                  00009580
      RETURN                                                               00009590
      END                                                                  00009600
C                                                                          00009610
 6000 REAL FUNCTION E2(B)                                                  00009620
      IMPLICIT REAL(A-Z)                                                   00009630
      INTEGER I,J,MPN,MIN                                                  00009640
C     FUNCTION TO EVALUATE EXPONENTIAL INTEGRAL WHERE B IS EFFECTIVE       00009650
C     CLEAR ATMOSPHERE OPTICAL THICKNESS                                   00009660
C                                                                          00009670
      DIMENSION TABLE2 (21,2)                                              00009680
      DATA TABLE2/.2,.22,.24,.26,.28,.32,.37,.36,.46,.50,.60,              00009690
```

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      0.62,.59,.58,.58,.58,.57,.56,.56,.58,.60,.5762,.5909,              00009700
      0.5703,.5375,.6070,.5671,.5515,.5150,.5109,.5017,.3070,            00009710
      0.3750,.3670,.3530,.3361,.3266,.3157,.3052,.2951,.2055,            00009720
      0.2702/                                                            00009730
C                                                                        00009740
C     FIND INTERVAL FOR B                                                00009750
      I=0                                                                00009760
 6010 I=I+1                                                              00009770
      IF(B-TABLE(I,1)) 6020,6100,6010                                    00009780
C     INTERPOLATION (LINEAR)                                             00009790
 6020 T2=TABLE(I-1,2)+(B-TABLE(I-1,1))/0.02*(TABLE(I-1,2)-TABLE(I,       00009800
     2))                                                                 00009810
      RETURN                                                             00009820
C     NO INTERPOLATION NECESSARY                                         00009830
 6100 T2=TABLE(I,2)                                                      00009840
      RETURN                                                             00009850
      END                                                                00009860
 7000 REAL FUNCTION WTRANS(SUM,ARRIVE,MODEL)                             00009870
      IMPLICIT REAL(A-Z)                                                 00009880
      PI=2.0*ARSIN(1.0)                                                  00009890
      COSFAC=COS(ARRIVE*PI/180.)                                         00009900
      VAR=SUM/COSFAC                                                     00009910
C     FIND VALUES OF INTEGRAL E1 FROM LOOKUP TABLE                       00009920
      TERM1=E1(SUM)                                                      00009930
      TERM2=E1(VAR)                                                      00009940
C     CALCULATE WATER TRANSMISSION COEFFICIENT FOR A DISPERSED           00009950
C     LIGHT SOURCE                                                       00009960
      WTRANS=MODEL*0.5*[illegible]*TERM1*[illegible] TERM2)+((1.-SUM)*EXP(-1.0*SUM)-(1.-V00009970
     $AR)*EXP(-1.0*VAR)*COSFAC)*2.)                                      00009980
      RETURN                                                             00009990
      END                                                                00010000
 7500 REAL FUNCTION E1(X)                                                00010010
      IMPLICIT REAL(A-Z)                                                 00010020
      INTEGER I,J,MPN,MIN                                                00010030
C     FUNCTION TO EVALUATE EXPONENTIAL INTEGRAL                          00010040
C                                                                        00010050
      DIMENSION TABLE(100,2)                                             00010060
      DATA TABLE/2.0,2.1,2.2,2.3,2.4,2.5,2.6,2.7,2.8,2.9,3.0,3.1,3.2,    00010070
     $3.3,3.4,3.5,3.6,3.7,3.8,3.9,4.0,4.1,4.2,4.3,4.4,4.5,4.6,4.7,4.8,   00010080
     $4.9,5.0,5.1,5.2,5.3,5.4,5.5,5.6,5.7,5.8,5.9,6.0,6.1,6.2,6.3,6.4,   00010090
     $6.5,6.6,6.7,6.8,6.9,7.0,7.1,7.2,7.3,7.4,7.5,7.6,7.7,7.8,7.9,8.0,   00010100
     $8.1,8.2,8.3,8.4,8.5,8.6,8.7,8.8,8.9,9.0,9.1,9.2,9.3,9.4,9.5,9.6,   00010110
     $9.7,9.8,9.9,10.,11.11,12.50,14.29,15.38,16.67,18.18,20.,.4890E-01, 00010120
     $.4261E-01,.3719E-01,.3250E-01,.2844E-01,.2491E-01,.2185E-01,.1918  00010130
     $E-01,.1686E-01,.1482E-01,.1305E-01,.1149E-01,.1013E-01,.8939E-02,  00010140
     $.7891E-02,.6970E-02,.6163E-02,.5448E-02,.4823E-02,.4267E-02,.3779  00010150
     $E-02,.3349E-02,.2969E-02,.2633E-02,.2336E-02,.2073E-02,.1841E-02,  00010160
     $.1635E-02,.1453E-02,.1292E-02,.1148E-02,.1021E-02,.9086E-03,       00010170
     $.8086E-03,.7198E-03,.6409E-03,.5708E-03,.5086E-03,.4532E-03,       00010180
     $.4039E-03,.3601E-03,.3211E-03,.2864E-03,.2555E-03,.2280E-03,       00010190
     $.2035E-03,.1816E-03,.1621E-03,.1448E-03,.1293E-03,.1155E-03,       00010200
     $.1032E-03,.9219E-04,.8239E-04,.7364E-04,.6583E-04,.5886E-04,       00010210
     $.5263E-04,.4707E-04,.4210E-04,.3767E-04,.3370E-04,.3016E-04,       00010220
     $.2699E-04,.2415E-04,.2162E-04,.1936E-04,.1733E-04,.1552E-04,       00010230
     $.1390E-04,.1245E-04,.1115E-04,.9990E-05,.8949E-05,.8018E-05,       00010240
     $.7185E-05,.6439E-05,.5771E-05,.5173E-05,.4637E-05,.4157E-05,       00010250
     $.1746E-07,.2778E-08,.4699E-09,.1208E-09,.1278E-10,.6650E-11,.4064E-12/ 00010260
```

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```
                                                             TS003.DSPOPN.FORT
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C                                                          00010270
C      FIND INTERVAL FOR Q                                 00010280
       I=0                                                 00010290
 7510  I=I+1                                               00010300
       IF(Q-TABLE(I,1)) 7520,7600,7510                     00010310
C      INTERPOLATION FOLLOWS                               00010320
 7520  E1=TABLE(I-1,2)+((Q-TABLE(I-1,1))/(TABLE(I,1)-TABLE(I-1,1)))*00010330
      1(TABLE(I-1,2)-TABLE(I,2))                           00010340
       RETURN                                              00010350
C      NO INTERPOLATION NECESSARY                          00010360
 7600  E1=TABLE(I,2)                                       00010370
       RETURN                                              00010380
       END                                                 00010390
```

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      REAL FUNCTION DSTRD2 (AG,TA,ARDW,ARFOV)                          00000010
C     THE FOLLOWING WILL CALCULATE THE DISTRIBUTION OF RADIANCE DUE TO 00000020
C     SIGNAL OR A NOISE MAKER.  TABLES ARE DEVELOPED IN TERMS OF ARFOV, 00000030
C     THE HALF-ANGLE OF RECEIVER FIELD OF VIEW.  LAYER1 REFERS TO ARFOV-00000040
C     15,LAYER2 REFERS TO ARFOV-20,LAYER3 REFERS TO ARFOV-25, LAYER4   00000050
C     REFERS TO ARFOV-30.                                              00000060
C                                                                      00000070
C                                                                      00000080
      IMPLICIT REAL (A-Z)                                              00000090
      INTEGER I,J,K                                                    00000100
C                                                                      00000110
      DIMENSION IMTA(19),IPHI0(13),TARG(13,19),LAYER1(13,19),          00000120
     1LAYER2(13,19),LAYER3(13,19),LAYER4(13,19),DSTRAD(13,19,4)        00000130
      EQUIVALENCE (LAYER1(1,1),DSTRAD(1,1,1)),(LAYER2(1,1),DSTRAD(1,1,2)00000140
     1),(LAYER3(1,1),DSTRAD(1,1,3)),(LAYER4(1,1),DSTRAD(1,1,4))        00000150
C                                                                      00000160
      DATA IMTA/0.,5.,10.,15.,20.,25.,30.,35.,40.,45.,50.,55.,60.,65., 00000170
     170.,75.,80.,85.,90./,IPHI0/15.,20.,25.,30.,35.,40.,45.,50.,55.,  00000180
     160.,65.,70.,75./                                                 00000190
C                                                                      00000200
C                                                                      00000210
      DATA LAYER1/.9999,.7904,.5996,.5019,.4,.33,.2600,.2,.1599,       00000220
     1.13,.1,.1,.1,.4661,.7656,.4643,.6167,.3622,.2712,.2105,          00000230
     1.1917,.1619,.1516,.1318,.1151,.1112,.6628,.5711,.4706,.3891,.3169,00000240
     1.2962,.2156,.1866,.1603,.1372,.1261,.1129,.1073,.4161,.3072,.3521,00000250
     1.3164,.2761,.2320,.1964,.1753,.1522,.1318,.1233,.1077,.1031,.1050,00000260
     1.2190,.2305,.2292,.2207,.1960,.1750,.1515,.1606,.1231,.1146,.1007,00000270
     1.0902,.0613,.0890,.1706,.1671,.1546,.1511,.1676,.1196,.1255,.1061,00000280
     1.1635,.0876,.0661,.0,.0731,.0504,.3766,.0911,.1057,.1106,.1052,  00000290
     1.1001,.0995,.0876,.0065,.0013,20.3,.0132,.0111,.0667,.0668,.0776, 00000300
     1.0042,.0015,.0796,.0713,.0771,.0717,30.0,.3051,.0231,.0151,.0668, 00000310
     1.0555,.0652,.0695,.0617,.0644,.0619,40.0,.0015,.0111,.0210,.0156, 00000320
     1.0476,.0456,.0528,.0574,.0517,50.0,.0014,.3000,.0165,.0766,.0154, 00000330
     1.0305,.0190,.0627,60.0,.0022,.0071,.0110,.0711,.0207,.0290,.0171, 00000340
     170.0,.0007,.0056,.0546,.0157,.0105,.0219,80.0,.0007,.0027,.0068,  00000350
     1.0102,.0150,90.0,.0006,.0075,.0056,.0091,100.0,.0005,.0022,.0040, 00000360
     1110.0,.0005,.0019,120.0,.0004,130.0/                             00000370
C                                                                      00000380
C                                                                      00000390
      DATA LAYER2/.9999,.9999,.8751,.7039,.6096,.5132,.4104,.3271,.20,  00000400
     1.26,.22,.2,.16,.4446,.4417,.6717,.6812,.5966,.6557,.3755,        00000410
     1.3290,.2806,.2464,.2207,.1942,.1899,.9229,.8118,.6900,.5905,.5077,00000420
     1.6230,.3602,.3111,.2706,.2302,.2198,.1906,.1860,.7110,.6256,.5441,00000430
     1.4917,.4337,.3827,.3308,.2918,.2516,.2205,.2006,.1816,.1751,.4164,00000440
     1.4105,.3926,.3766,.3409,.3109,.2865,.2629,.2327,.2159,.1909,.1775,00000450
     1.1655,.1921,.2357,.2578,.2611,.2610,.2551,.2429,.2227,.2072,.1934,00000460
     1.1766,.1636,.1565,.0625,.0958,.1397,.1424,.1803,.1669,.1934,.1867,00000470
     1.1767,.1602,.1570,.1509,.1639,.0,.0200,.0574,.0010,.1390,.1251,  00000480
     1.1300,.1392,.1461,.1404,.1314,.1790,.1272,20.0,.0137,.3351,.3570, 00000490
     1.0777,.0804,.1036,.1307,.1174,.1112,.1098,.1064,30.0,.3051,.0715, 00000500
     1.0613,.0584,.0612,.0705,.0061,.0925,.0917,.0927,40.0,.0040,.3159, 00000510
     1.0290,.0432,.0527,.0591,.0654,.0711,.0769,50.0,.0014,.0100,.0195, 00000520
     1.0206,.0681,.0600,.0515,.0508,60.0,.0027,.0077,.0157,.0261,.0118, 00000530
     1.0162,.0417,70.0,.0311,.1057,.0130,.0177,.0225,.0270,80.0,.0007, 00000540
     1.0039,.0209,.0142,.0169,90.0,.0006,.0025,.0057,.0100,130.0,.0005, 00000550
     1.0027,.0050,110.0,.0305,.0019,120.0,.0004/                       00000560
C                                                                      00000570
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C                                                                       00000580
      DATA LAYER1/.9999,.9999,1.,.92,.0000,.65,.59,.58,.52,             00000590
     1.37,.33,.29,.26,.9999,.9999,.9641,.8731,.7610,.6400,.5512,        00000600
     [illegible]                                                        00000610
     1.6003,.5106,.4936,.3970,.3575,.3237,.2870,.2762,.9131,.8337,.7367,00000620
     1.8610,.3239,.5361,.4699,.4222,.3770,.3447,.3075,.2794,.2624,.7290,00000630
     1.6630,.5016,.5341,.4919,.4510,.4174,.3806,.3439,.3150,.7038,.2679,00000640
     1.2510,.4527,.4366,.4200,.4310,.3042,.3696,.3504,.3251,.3110,.2873,00000650
     1.2634,.2672,.2163,.2390,.2632,.2714,.2750,.2010,.2827,.2706,.2706,00000660
     [illegible]                                                        00000670
     1.2092,.2113,.2371,.2036,.2070,.1919,.1888,.5,.0200,.0597,.0895,   00000680
     1.1179,.1350,.1520,.1636,.1692,.1697,.1705,.1705,.1696,20.0,       00000690
     1.0125,.0350,.0601,.3000,.0990,.1117,.1730,.1330,.1319,.1397,      00000700
     1.1357,30.0,.0051,.0219,.0411,.0620,.0730,.0890,.1036,.1070,       00000710
     1.1130,.1150,40.0,.0051,.0107,.0333,.0462,.0575,.0661,.0702,       00000720
     [illegible]                                                        00000730
     1.3600,60.0,.0022,.0091,.0186,.0257,.3362,.0619,.0680,70.0,        00000740
     1.0011,.0371,.0160,.3100,.3257,.0119,80.0,.0010,.0019,.3067,       00000750
     1.0151,.0205,90.0,.0009,.0036,.0079,.0119,100.0,.0005,.0024,.3056, 00000760
     0110.0,.0005,.3021/                                                00000770
C                                                                       00000780
C                                                                       00000790
      DATA LAYER4/.9990,.9999,1.,1.,.9617,.0057,.7217,.6121,.56,.5,     00000800
     1.96,.4,.37,.9999,.9999,1.,.9797,.7305,.0060,.7392,.6267,          00000810
     1.5505,.4962,.4531,.4016,.3039,.9999,.9999,.9711,.9077,.8191,.7673,00000820
     1.0766,.5967,.5361,.4034,.4402,.4073,.3760,.9999,.9679,.0000,.8103,00000830
     1.7609,.6007,.6120,.5667,.4994,.4571,.4201,.3034,.3630,.9171,.8669,00000840
     [illegible]                                                        00000850
     [illegible]                                                        00000860
     1.3317,.3175,.4026,.4079,.4169,.4204,.4007,.3916,.3015,.3667,.3525,00000870
     1.3190,.3266,.3321,.2991,.2686,.2565,.2027,.2922,.3026,.3019,.3031,00000880
     1.2903,.2965,.2009,.2002,.2600,.2581,.0610,.3052,.1559,.1015,.2071,00000890
     1.2204,.2306,.2115,.2101,.2139,.2160,.2177,.2285,.0,.0270,.0609,   00000900
     [illegible]                                                        00000910
     [illegible]                                                        00000920
     110.0,.0037,.0240,.0466,.0661,.0806,.0964,.1007,.1192,.1739,.1790, 00000930
     140.0,.0051,.0191,.0330,.0571,.0656,.0715,.0060,.0956,.0979,50.0,  00000940
     1.0030,.0111,.0256,.0367,.0405,.0616,.0652,.0755,60.0,.0022,.0091, 00000950
     1.0190,.0293,.0306,.0651,.0591,70.0,.0011,.0006,.0157,.0221,.0275, 00000960
     1.0350,80.0,.0010,.0039,.0096,.0159,.0215,90.0,.0009,.0036,.0079,  00000970
     1.0136,100.0,.0008,.0312,.00587                                    00000980
      I=0                                                               00000990
      J=0                                                               00001000
      DSTRD2=-100.                                                      00001010
      ANGLE=10.                                                         00001020
C     INITIALIZE ARRAY DIMENSIONS AND VALUE OF ANGLE FOR LOOP 10        00001030
C     INITIALIZE VALUE TO BE RETURNED                                   00001040
      IFLAG=0.0                                                         00001050
      JFLAG=0.0                                                         00001060
      ZFLAG=0.0                                                         00001070
C     INITIALIZE FLAGS FOR ERROR NOTIFICATION.                          00001080
C                                                                       00001100
    2 IF(ANLIA.LT.0.5.OR.ANLIA.GT.90.0)JFLAG=1.0                        00001110
    4 IF(ARDW.LT.15.0.OR.ARDW.GT.75.0)IFLAG=1.0                         00001120
    6 IF(ARFOV.NE.15.0.AND.ARFOV.NE.23.3.AND.ARFOV.NE.25.3.AND.         00001130
     1ARFOV.NE.30.0)ZFLAG=1.0                                           00001140
    8 IF(IFLAG.EQ.1.0.OR.JFLAG.EQ.1.0.OR.ZFLAG.EQ.1.0)GO TO 9990        00001150
```

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```
C     CHECK TO SEE IF PARAMETERS ARE WITHIN RANGES SPECIFIED
C
C
   10 J=J+1
      IF(ADELTA-FDELTA(J))20,20,10
C     FIND NECESSARY RANGE FOR INTERPOLATION OF ADELTA
C
   20 I=I+1
C     CALCULATE VALUE OF NUMERATOR FOR INTERPOLATION
      IF(ABSPHI-TPHIO(I))30,30,20
C     FIND SMALLEST TPHIO .GE. ABPHI FOR CALCULATION
C
   30 DO 90 Z=1,6
      ANGLE=ANGLE+5.
      IF(ARFOV.EQ.ANGLE)GO TO 1000
C     DETERMINE VALUE OF ARFOV
   90 CONTINUE
C
C
 1000 NUM=5.-(FDELTA(J)-ADELTA)
      IF (NUM.EQ.5.0)GO TO 2000
C
 1500 DSTRD2=NUM/5.0*(DSTRADE(I,J,Z)-DSTRADE(I,J-1,Z))+DSTRADE(I,J-1,Z)
C     THIS STATEMENT PERFORMS ACTUAL INTERPOLATION
C
      RETURN
C
C
 2000 DSTRD2=DSTRADE(I,J,Z)
C     NO INTERPOLATION IS NECESSARY.
      RETURN
C
C
 9990 WRITE(6,9999)
 9999 FORMAT(1X,'THERE IS AN ERROR IN PARAMETERS.  DSTRD2 RETURNS DEFAUL
     1T VALUE OF -100.0')
99999 RETURN
      END
```

4.5 MODEL UNCERTAINTIES

The sub-models contained in Section 4.3 have a number of uncertainties, due to a lack of experimental work. (The uncertainties in the signal models was discussed in Section 3.3.)

4.5.1 Average Power Transmission

Two additional undertainties arise in the models in Sections 4.3.1, 4.3.2, 4.3.3, 4.3.4, 4.2.6, and 4.2.7, in addition to those present in the signal energy transmission models.

Clear atmosphere transmission for solar or lunar zenith angles greater than 85° is not correctly given in the SPDPM.

Air-water interface transmission for solar or lunar zenith angles greater than 85° is also not correctly given in the SPDPM.

The importance of these two inaccuracies is undetermined, until we estimate how often such conditions apply to the scenario. This will be done in future work.

4.5.2 Angular Effects

The same uncertainty effects apply here as for the signal angular effects.

4.5.3 Temporal Effects

At present all the background sources in the SPDPM are taken as steady state. The bioluminescent background may have enough temporal structure to invalidate this model, but no definitive results exist at present.*

Table 4-10 summarizes the uncertainty status of the noise portion of the SPDPM.

*Again, a pulse distorting filter is not treated in these sub-models. Should it become the leading candidate for the optical filter, the temporal sub-model would need modification.

Table 4-10. Status of Noise Portion Models of SPDPM

	THIN CLOUD	THICK CLOUD	COMMENTS ON EXPERIMENTAL WORK REQUIRED
AVERAGE POWER TRANSMISSION			
Clear Atmosphere	Partailly verified	Not applicable	Large zenith angle problems. Impact TBD.
Cloud	Unknown but small effect	Unknown	Signal experiment applicable. Large zenith angle effects TBD.
Cloud to Water	Not applicable	OK	None
Air-Water Interface	Partially verified	OK	Large zenith problems. Impact TBD.
Water	Unknown	Unknown	A signal experiment would be applicable.
ANGULAR EFFECTS			
Shape	Partially verified	Partially verified	Should be done.
Out-of-Water Contribution	OK	Partially verified	Should be done if other related work is planned.
Air-Water Interface	OK	OK	None
In-Water Contribution	Partially verified	Partially verified	Needed for depth and water type.
Combination of Effects	Partially verified	Unknown	Needed
TEMPORAL EFFECTS			
Bioluminescence	Temporal character unknown as a function of depth, location, submarine speed, season. Some experimental work is needed.		

4.6 PARAMETER VALUE UNCERTAINTIES

In addition to those parameter value uncertainties discussed in Section 3.5 for the signal portion of the SPDPM, the noise portion parameters are uncertain with regard to background levels.

The solar and lunar parameters are not uncertain. The effective strength of the blue skylight background (and its solar zenith angle dependence) is uncertain and requires clarification. It has a significant impact since for thick cloud conditions the system may be skylight limited at high latitudes.

The starlight/zodiacal light parameters are not in question.

The strength of the bioluminescence is very uncertain, as is its distribution in depth, season, time of night, location, and its response to stimulation such as submarine motion. This is important since for the value of 10^{-3} watts/(m^2-micron) used in the SPDPM the system is bioluminescent limited for many water and cloud conditions.

Table 4-11 summarizes the uncertainty status of the "parameter" values for the noise portion of the channel characterization.

Table 4-11. Status of "Input Parameters" to the Noise Portion of the SPDPM

PARAMETER	STATUS	COMMENTS ON EXPERIMENTAL WORK REQUIRED
Clear Atmosphere	OK	None
<u>Cloud:</u>		
$\langle\cos\theta\rangle$	OK	None
θ	OK	None
ω_o	Partially known	No direct experiment possible
τ_c	Partially known	Some work is planned during first cloud experiment. Equipment may be too inaccurate for good results.
T	Partially known	Interpretation of data required.
Cloud-to-Water	OK	None
Air Water Interface	OK, for low wind speeds	Some required for bad conditions.
<u>Water:</u>		
k_i	Partially known	Required if not done by other contractors.
D_i	Partially known	Required if available data not able to be interpreted.
[illegible]$_{sl}$	Partially known	Required as a function of depth and water type.
S	Partially known	May become available for surface water from ongoing work. Needed for water at depth.
n	OK	None
<u>Background Levels:</u>		
Blue Skylight	Partially known	Needed
Bioluminesence	Unknown	Needed

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Section 5

DOWNLINK COMMUNICATION MODEL

This section discusses the model for the optical communication link from a satellite to a submerged submarine. The section is organized as follows:

5.1 Downlink Communications Model-Philosophy and Flow Chart

5.1.1 Philosophy of Approach - Downlink Communication Model

5.1.2 Model Flow Chart - Downlink Communication Model

5.2 Input Information

5.2.1 Environment

5.2.2 Requirements

5.2.3 System Design

5.3 Sub-Models

5.3.1 Area Relationships

5.3.2 Temporal Relationships

5.3.3 Message

5.3.4 Modulation/Demodulation

5.3.5 Scanning Relationships

5.3.6 Receiver and Source

5.3.7 Availability/System Effectiveness and Adaptive Scanning

5.4 Computer Program for the DCM

5.4.1 Introduction

5.4.2 Names of Variables

5.4.3 Listing

5.5 Model Uncertainties

5.5.1 Area Relationships

5.5.2 Temporal Relationships

5.5.3 Message

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5. (Continued)

5.1 Downlink Communications Model-Philosophy and Flow Chart

This section explains the basic approach used in the detailed models presented in Section 5.3, and presents flow charts showing the interrelationships of the sub-models and their required inputs. (These inputs are discussed in more detail in Section 5.2.)

5.1.1 Philosphy of Approach-Downlink Communications Model

This model is an intermediate step between the Single Pulse Downlink Propagation Model (SPDPM) and the Full OSCAR Communication System architecture. We have therefore used the approach that:

1. The SPDPM is fully available for use:

2. This Downlink Communication Model (DCM) treats the problem of communicating to a specific area by a single satellite within a single time interval. It does not consider the entire OSCAR coverage area, a complete satellite constellation suitable for covering that area, the system effectiveness of any part but the downlink communication link of the OSCAR system, etc. As such it is a building block in the complete system architecture just as the SPDPM is a building block within this Downlink Communication Model.

3. For a given interval of time, the full OSCAR system requirements must be met. During this time interval, the satellite location, sun location, and moon location are completely specified. In addition, the area which must be communicated with is described both geometrically and with regard to its complete propagation environment;

4. The coverage area is resolved into equal-area resolution elements, each with a uniform value of the environmental parameters and each small enough so that signal and background zenith angle effects vary negligibly across the element. Then each element is represented by a mean value of latitude and longitude and the SPDPM is evaluated at that point, with results which apply throughout the resolution element.

5. A single system design is tested to see how well it meets OSCAR requirements. Besides all the normal transmitter and receiver hardware parameters, this system design considers:

5.1.1 (Continued)

a. The satellite location

b. The choice of demodulation technique(s)

c. The choice of post-detection processing for anti-jam of time-of-peak demodulation

d. The choice of scan technique.

6. This system design includes consideration of all the times involved, including source warm-up time, dead-time between frames, slot widths, and time to slew to a new spot.

7. The minimum spot dimensions are dependent on their overlap, the adjacent spot revisit time, the satellite short and long term pointing jitter, the scan technique and the total time allowed to cover the area.

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5.1.2 Model Flow Chart-Downlink Communication Model

A schematic of the overall Downlink Communication Model is shown in Figure 5-1. The input parameters are designated as environment, requirements, and system design. Using these inputs, area relationships and receiver parameters (chiefly the value of δ, the angle between receiver axis and the incoming beam) are developed. In parallel, source parameters (like required prime power), message, and modulation/demodulation equations are evaluated. The modulation/demodulation and area relationship results are used to determine the scanning parameters, and then all the parameters are used as inputs to the availability analysis. Finally, temporal relationships (like the source on-time) are evaluated from the source and availability results.

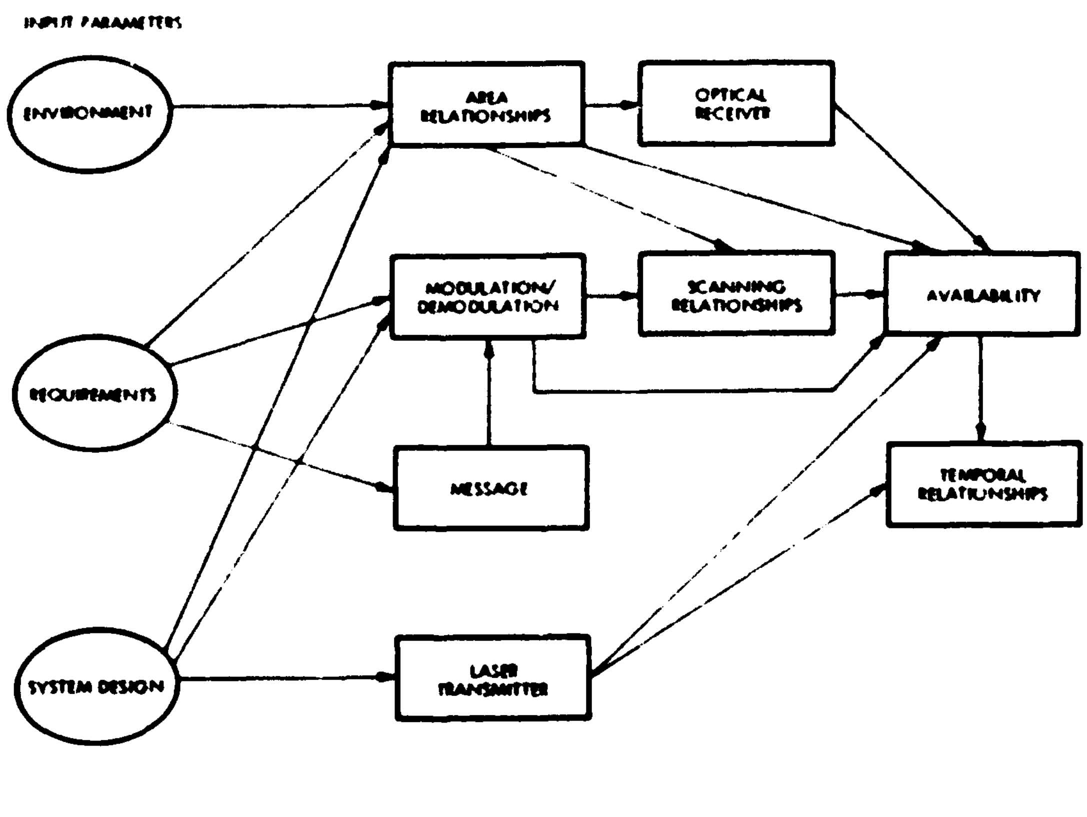

Figure 5-1. Schematic of Downlink Communication Model

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5.1.2 (Continued)

Figure 5-2 is a detailed flow chart showing all the calculations to be performed in this model:

(I) The input parameters are listed in the three ellipses on the left hand side of the figure, including environment, requirements, and system design. (The symbols are defined in the glossary in Section 2, and also in the input discussions in Section 5.2).

(II) The only additional input is the nominal $\tau_{OPT} = 50$ value, shown in the ellipse near the center, and used in the partially adaptive scanning analysis.

(III) The calculation equations are represented by the rectangular boxes. Within each box is the symbol for the parameter to be calculated and the equation number (from Section 5.3) for the equation to be used to calculate the parameter.

(IV) SPDPM within a rectangular box refers to the full single pulse downlink propagation model.

(V) The diamond shaped boxes represent branch points. Only one of the two (or three) paths coming out of the diamond are followed, depending on the value of the parameters (or input choice). The branching parameters include τ_{OPT}, Threshold or Time-of-Peak Demodulation, Anti-Jam Processing for Time-of-Peak Demodulation, q, T_{TOT} vis-a-vis T_A, and scan technique.

(VI) Key outputs of the program include P'_{TOT}, total satellite prime power; A_{VL}, availability or system effectiveness; N_{SP}, the number of spoofing events per year; N_J (or N'_J), the number of jamming events per year; and N_{PL}, the number of pulses used by a given laser transmitter to achieve the A_{VL}.

(FIGURE LOCATED IN ENVELOPE IN REAR OF BOOK)

Figure 5-2. Flow Diagram of Downlink Communication Model

5.2 Input Information

This section discusses the form and units of the required inputs to the down-link communication model. These inputs are divided into three categories, as seen in the computer flow charts: Environment, Requirements, and System Design.

5.2.1 Environment

All the Single Pulse Downlink Propagation Model (SPDPM) environmental inputs are required here since the SPDPM will be extensively utilized. These inputs include b, T, σ_c, $<\cos\theta>$, ω_0, θ, H, V, n, k_i, D_i, θ_{S1}, s, $\theta_{S/2}$, L_S, $\theta_{m/2}$, L_m, L_B, L_Z, and L_{BL}.

Other and new environmental parameters are:

SYMBOL	DESCRIPTION	UNITS
A_{RE}	Area of a single resolution element	$(\text{Meter})^2$
R_{SU}	Distance from sun to receiver	Meters
α_{SU}	Solar latitude	Degrees
β_{SU}	Solar longitude	Degrees
R_E	Mean Earth Radius	Meters
R_{MU}	Distance from moon to receiver	Meters
α_{MU}	Lunar latitude	Degrees
β_{MU}	Lunar longitude	Degrees

5.2.2 Requirements

All the Statement of Work requirements are entered here in their most elemental form:

SYMBOL	DESCRIPTION	UNITS
T_A	Coverage Time	Seconds
Coverage Area	That area for which a given satellite is assigned responsibility for the time interval T_A. The boundaries should be specified in latitude and longitude.	-

5.2.2 (Continued)

SYMBOL	DESCRIPTION	UNITS
M_{LO}	The message length, i.e., the number of bits which must be broadcast to the entire coverage area within T_A.	Bits
N_M	The number of missed messages per year. (This is the quality of service requirement)	$(\text{Year})^{-1}$
N_{SPi}	The number of spoofing events per year.	$(\text{Year})^{-1}$
N_{Ji}	The number of jamming events per year.	$(\text{Year})^{-1}$
g	The ratio of threat "cost" to our system "cost."	-
D	Submarine Depth	Meters

5.2.3 System Design

All the SPDPM system design inputs are required here since it will be extensively utilized. These inputs include q, γ_T, θ_R, γ_R, d, B_{OPT}, (kT), F_A, G, $(\eta e/h\nu)$, R_L, I_d and F.

Other and new system design parameters are:

SYMBOL	DESCRIPTION	UNITS
t_{Si}	Slew time, scan time or dead time between illuminated spots.	Seconds
t_W	Source warm-up time, before it is ready for full operation.	Seconds
PRF	Source repetition frequency	$(\text{Seconds})^{-1}$, or Hz
G_{EL}	Off-zenith in-water receiver pointing angle, which may be different in each resolution element.	Degrees
G_{AZ}	Azimuth receiver pointing angle, relative to the local longitude.	Degrees

5.2.3 (Continued)

SYMBOL	DESCRIPTION	UNITS
m	Number of simultaneously active lasers aboard the satellite.	-
E_p	Energy per pulse of each active laser aboard the satellite.	Joules
F_L	"Wallplug" laser efficiency	-
P'_{HO}	Prime-power on the satellite required for all non-laser functions.	Watts
R_S	Satellite altitude	Meters
λ_S	Satellite latitude	Degrees
β_S	Satellite longitude	Degrees
t_f	Dead time between frames	Seconds
t_s	Slot width	Seconds
ℓ	Number of bits per pulse	-
ϵ	Overlap factor between illuminated spots	-
σ_{TS}	Satellite rms short term angular jitter	Radians
σ_{TDR}	Satellite rms long term angular drift	Radians
Demodulation Approach	Choice of threshold exceedance or time-of-peak demodulation approach	-
Post Detection Processing for Time-of-Peak Demodulation	Choice of post-detection processing approach to provide anti-jamming capability for time-of-peak demodulation approach.	-
Scanning Approach	Choice of totally non-adaptive scan, one partially adaptive scan, or fully adaptive scan technique.	-

5.3 Sub-Models

This section develops all the equations used in the calculation of the performance of the communication downlink.

Section 5.3.1 considers the area relationship and develops the concept of resolution elements.

Section 5.3.2 considers the temporal relationships and Section 5.3.3 considers relationships derived from the message parameters.

Section 5.3.4 develops the modulation/demodulation relationships for pulse position modulation, both threshold and time-of-peak demodulation, and derives signal to noise and message structure requirements for quality of service, spoofing and jamming.

Section 5.3.5 develops scanning relationships while Section 5.3.6 considers new receiver and laser transmitter parameters.

Section 5.3.7 develops equations for system availability, for non-adaptive and adaptive scanning.

5.3.1 Area Relationships

The input to the downlink communication system model will include the location of the satellite terminal and the location and extent of the area it is responsible for communicating with. All the angular information will be input in terms of latitude and longitude. We therefore define, as exemplified in Figure 5-3:

- R_S Satellite altitude
- R_E Mean earth radius
- λ_S Satellite latitude
- λ_{SU} Sun's latitude
- λ_{MU} Moon's latitude
- λ_{Ai} Latitude of point within coverage area
- ϕ_S Satellite longitude
- ϕ_{SU} Sun's longitude
- ϕ_{MU} Moon's longitude
- ϕ_{Aj} Longitude of point within coverage area.

From these input parameters we need to derive

- R Range from satellite to submarine
- θ_S Signal zenith angle into the water
- θ_{SU} Solar zenith angle into the water
- θ_{MU} Lunar zenith angle into the water.

It is straightforward to derive the range by expressing the satellite location and submarine location in cartesian coordinates with the origin at the center of the earth.

$$R^2 = (X_S - X_E)^2 + (Y_S - Y_E)^2 + (Z_S - Z_E)^2 \qquad (5\text{-}1)$$

5.3.1 (Continued)

for

$X_E = R_E \cos \alpha_{Ai} \cos \beta_{Aj}$, (5-1a)	$X_S = (R_E + R_S) \cos \alpha_S \cos \beta_S$, (5-1d)
$Y_E = R_E \cos \alpha_{Ai} \sin \beta_{Aj}$, (5-1b)	$Y_S = (R_E + R_S) \cos \alpha_S \sin \beta_S$, (5-1e)
$Z_E = R_E \sin \alpha_{Ai}$; (5-1c)	$Z_S = (R_E + R_S) \sin \alpha_S$. (5-1f)

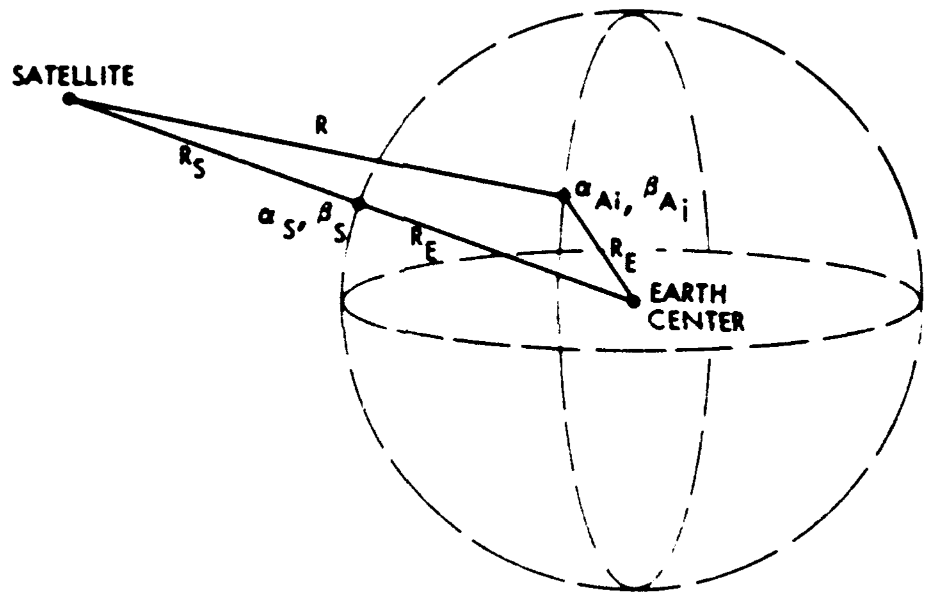

Figure 5-3. Latitude and Range Satellite to Earth Geometry

5.3.1 (Continued)

The expression becomes, after substitution and manipulation,

$$R_{ij} = \left[(R_E+R_S)^2 + R_E^2 - R_E(R_E+R_S)\left\{\cos(\alpha_{Ai}+\alpha_S)\left(\cos(\beta_{Aj}-\beta_S)-1\right) + \cos(\alpha_{Ai}-\alpha_S)\left(\cos(\beta_{Aj}-\beta_S)+1\right)\right\}\right]^{1/2} \tag{5-2}$$

From Figure 5-4, the zenith angle into the water for the signal is given by

$$\theta_S = \pi - \psi, \tag{5-3}$$

for

$$R^2 = (R_E + R_S)^2 - R_E^2 + 2\, R_E\, R \cos \psi. \tag{5-4}$$

Comparing (5-3) and (5-4) it is evident that

$$\theta_{S_{ij}} = \cos^{-1}\left\{\frac{1}{R}\left[\left(\frac{R_E+R_S}{2}\right)\left\{\cos(\alpha_{Ai}+\alpha_S)[\cos(\beta_{Aj}-\beta_S)-1] + \cos(\alpha_{Ai}-\alpha_S)[\cos(\beta_{Aj}-\beta_S)+1]\right\} - R_E\right]\right\} \tag{5-5}$$

By analogy, for the solar zenith angle (since $R_{SU} >> R_E$)

$$\theta_{SU_{ij}} = \cos^{-1}\left\{\frac{1}{2}\left\{\cos(\alpha_{Ai}+\alpha_{SU})\left[\cos(\beta_{Aj}-\beta_{SU})-1\right] + \cos(\alpha_{Ai}-\alpha_{SU})\left[\cos(\beta_{Ai}-\beta_{SU})+1\right]\right\}\right\} \tag{5-6}$$

and for the lunar zenith angle (since $R_{MU} >> R_E$)

$$\theta_{MU_{ij}} = \cos^{-1}\left\{\frac{1}{2}\left\{\cos(\alpha_{Aj}+\alpha_{MU})\left[\cos(\beta_{Aj}-\beta_{MU})-1\right] + \cos(\alpha_{Ai}-\alpha_{MU})\left[\cos(\beta_{Ai}-\beta_{MU})+1\right]\right\}\right\} \tag{5-7}$$

These angular expressions must also be interpreted in terms of an area to be covered. We assume the following propagation path inputs over the coverage area:

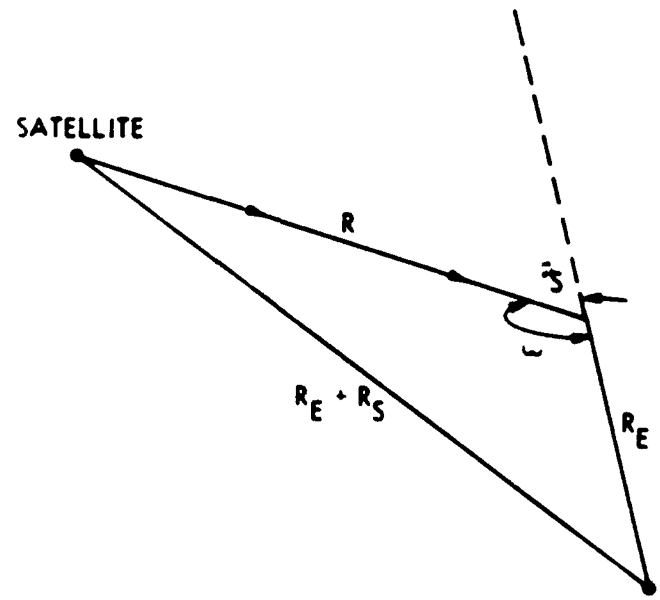

Figure 5-4. Signal Zenith Entrance Angle Geometry

5.3.1 (Continued)

1. There are four areas of importance in the OSCAR scenario:

   a. The total area in the OSCAR requirement which must be communicated with during the time interval;

   b. The area which a single satellite is assigned to cover during a single time interval. It is this area which is considered in this Downlink Communication Model (DCM), and which we designate A_I;

   c. The single satellite/single time interval coverage area A_I is divided into environmental resolution elements, of area A_{RE}, each of which has a uniform value of all parameters related to the environment's effects on both the signal and background propagation;

   d. The area of a single illuminated spot, which will ordinarily be much less than A_{RE}, and which will be determined in later sections.

These four areas are illustrated in Figure 5-5.

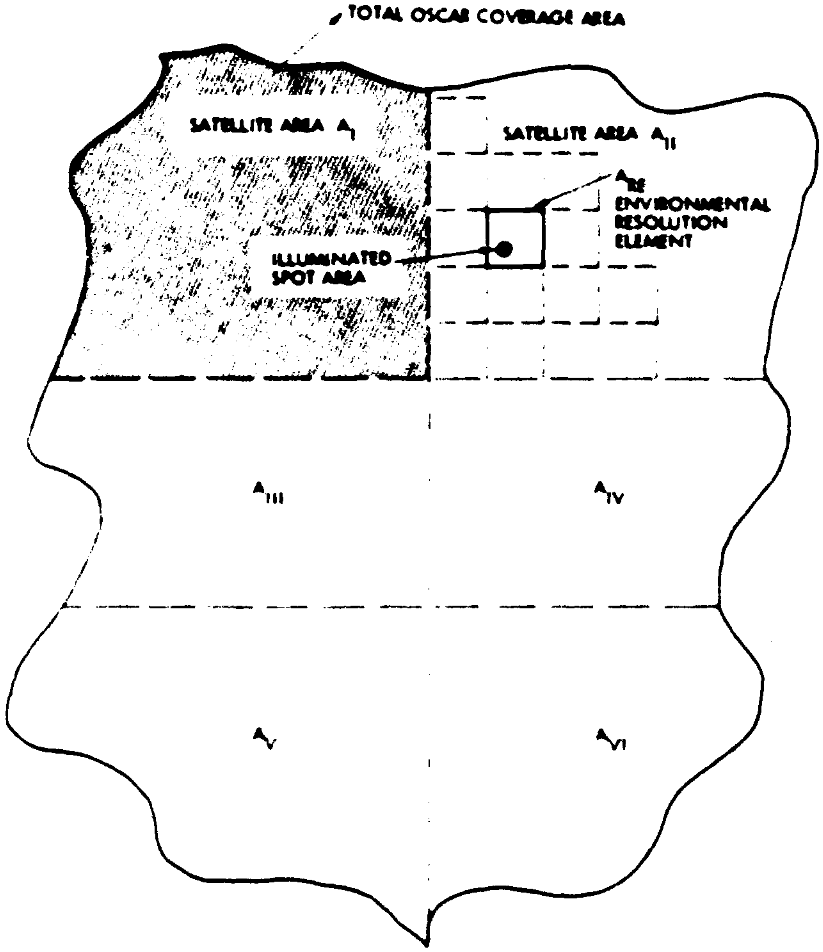

Figure 5-5. Illustration of Four Area Relations

5.3.1 (Continued)

2. Each resolution element is much larger than the smallest possible illuminated spot area, but small enough to allow for essential signal level equality due to signal and/or background zenith angle alone within the element, if the environmental effects are uniform over the entire coverage area;

5.3.1 (Continued)

3. Each resolution element is bounded by constant latitude/constant longitude lines. The four corners of resolution element are then given by (for the first element in the coverage area, for example)

$$1^{\alpha}A,\ 1^{\beta}A;\ 1^{\alpha}A,\ 2^{\beta}A;$$

$$2^{\alpha}A,\ 1^{\beta}A;\ 2^{\alpha}A;\ 2^{\beta}A.$$

4. The entire resolution element is characterized by its mean value of latitude and longitude, and it is this value $(\alpha_{Ai}, \beta_{Aj})$ which is used in all Single Pulse Propagation Model calculations. The mean values are defined by

$$\alpha_i = \frac{1}{2} \left(i^{\alpha}A + i{+}1^{\alpha}A \right) \qquad (5\text{-}8)$$

and

$$\beta_j = \frac{1}{2} \left(j^{\beta}A + j{+}1^{\beta}A \right) \qquad (5\text{-}9)$$

In this way the number of calculations (required to characterize operation over the full area with possible adaptive scan coverage) are minimized.

5. Each resolution element within the coverage area contains the same area.

6. This area shall have the same width in longitude, independent of latitude. Its angular dimension in latitude shall be varied to maintain equal areas.

The approximate area of a figure bounded by constant latitude and longitude is given by

$$A_{RE} = [R_E(\alpha_2 - \alpha_1)]\left[R_E(\beta_2 - \beta_1)\cos\left(\frac{\alpha_2 + \alpha_1}{2}\right)\right] \qquad (5\text{-}10)$$

5.3.1 (Continued)

To insure that the resulting resolution elements will not assume distorted shapes at either latitude extreme, we demand that it be approximately symmetric at the mid-latitude value, or

$$R_E\,(\alpha_2-\alpha_1) = R_E\,(\beta_2-\beta_1)\cos\left(\frac{\alpha_2+\alpha_1}{2}\right) \quad \text{at} \quad \frac{\alpha_2+\alpha_1}{2} = 45^0,$$

or,

$$\Delta\alpha = \Delta\beta\cos\left(\frac{\alpha_2+\alpha_1}{2}\right) \quad \text{at} \quad \frac{\alpha_2+\alpha_1}{2} = 45^0,$$

or

$$\Delta\alpha = \frac{\Delta\beta}{\sqrt{2}}\,. \tag{5-11a}$$

Putting (5-11a) into (5-10) at $\frac{\alpha_2+\alpha_1}{2} = 45^0$ we find

$$\frac{(\Delta\beta)^2}{2} = \frac{A_{RE}}{R_E^2}\,,$$

or

$$\Delta\beta = \frac{[2\,A_{RE}]^{1/2}}{R_E}\,. \tag{5-11b}$$

We have solved (5-11b) for $A_{RE} = 3(10^{11})m^2$, $2(10^{11})m^2$, $1(10^{11})m^2$ and $5(10^{10})m^2$ and listed the results in Table 5-1. Also shown in Table 5-1 are the values of the corresponding latitude boundaries as the latitude is stepped off from 0^0 to 70^0, and the length of each side of the resolution element.

The spot sizes themselves are much smaller than these resolution elements. If we maintain a circular spot independent of signal zenith angle, its diameter will be given by

$$D_{SP} = R\theta_T \tag{5-11c}$$

Table 5-1. Resolution Element Angular Coordinates

$$\alpha_i \quad \begin{bmatrix}\text{Vertical Dimension (m)}\\ \text{Horizontal Dimension (m)}\end{bmatrix}$$

A_{RE}

$3(10^{11})m^2$	$2(10^{11})m^2$	$1(10^{11})m^2$	$5(10^{10})m^2$
$\Delta\psi$ = 0.1215 (6.96°)	$\Delta\psi$ = 0.0991 (5.68°)	$\Delta\psi$ = 0.0701 (4.01°)	$\Delta\psi$ = 0.0496 (2.84°)
3.48° $\begin{bmatrix}3.866\times10^5\\7.7\end{bmatrix}$	2.84° $\begin{bmatrix}3.158\times10^5\\6.3\end{bmatrix}$	2.01° $\begin{bmatrix}2.232\times10^5\\4.46\end{bmatrix}$	1.41° $\begin{bmatrix}1.577\times10^5\\3.157\end{bmatrix}$
6.97° $\begin{bmatrix}3.88\\7.72\end{bmatrix}$	5.68° $\begin{bmatrix}3.166\\6.3\end{bmatrix}$	4.028° $\begin{bmatrix}2.23\\4.4\end{bmatrix}$	2.84° $\begin{bmatrix}1.578\\3.16\end{bmatrix}$
10.49° $\begin{bmatrix}3.9\\7.69\end{bmatrix}$	8.556° $\begin{bmatrix}3.18\\6.287\end{bmatrix}$	6.0° $\begin{bmatrix}2.24\\4.456\end{bmatrix}$	4.26° $\begin{bmatrix}1.58\\3.15\end{bmatrix}$
14.049° $\begin{bmatrix}3.95\\7.656\end{bmatrix}$	11.44° $\begin{bmatrix}3.206\\6.266\end{bmatrix}$	8.06° $\begin{bmatrix}2.25\\4.45\end{bmatrix}$	5.68° $\begin{bmatrix}1.58\\3.15\end{bmatrix}$
17.665° $\begin{bmatrix}4.017\\7.6\end{bmatrix}$	14.356° $\begin{bmatrix}3.239\\6.24\end{bmatrix}$	10.1° $\begin{bmatrix}2.26\\4.44\end{bmatrix}$	7.1° $\begin{bmatrix}1.58\\3.15\end{bmatrix}$
21.355° $\begin{bmatrix}4.089\\7.536\end{bmatrix}$	17.3° $\begin{bmatrix}3.282\\6.2\end{bmatrix}$	12.146° $\begin{bmatrix}2.275\\4.425\end{bmatrix}$	8.56° $\begin{bmatrix}1.59\\3.14\end{bmatrix}$
25.14° $\begin{bmatrix}4.2\\7.45\end{bmatrix}$	20.3° $\begin{bmatrix}3.336\\6.158\end{bmatrix}$	14.2° $\begin{bmatrix}2.29\\4.41\end{bmatrix}$	9.99° $\begin{bmatrix}1.598\\3.14\end{bmatrix}$
29.046° $\begin{bmatrix}4.34\\7.35\end{bmatrix}$	23.375° $\begin{bmatrix}3.4\\6.1\end{bmatrix}$	16.29° $\begin{bmatrix}2.31\\4.39\end{bmatrix}$	11.43° $\begin{bmatrix}1.6\\3.13\end{bmatrix}$
33.31° $\begin{bmatrix}4.5\\7.23\end{bmatrix}$	26.5° $\begin{bmatrix}3.48\\6.046\end{bmatrix}$	18.4° $\begin{bmatrix}2.34\\4.37\end{bmatrix}$	12.89° $\begin{bmatrix}1.61\\3.128\end{bmatrix}$
37.366° $\begin{bmatrix}4.73\\7.08\end{bmatrix}$	29.73° $\begin{bmatrix}3.58\\5.97\end{bmatrix}$	20.5° $\begin{bmatrix}2.38\\4.35\end{bmatrix}$	14.3° $\begin{bmatrix}1.62\\3.12\end{bmatrix}$
41.88° $\begin{bmatrix}5.02\\6.83\end{bmatrix}$	33.06° $\begin{bmatrix}3.7\\5.88\end{bmatrix}$	22.69° $\begin{bmatrix}2.4\\4.32\end{bmatrix}$	15.8° $\begin{bmatrix}1.63\\3.11\end{bmatrix}$

Table 5-1. Resolution Element Angular Coordinates (Continued)

A_{RE}

$3(10^{11})m^2$	$2(10^{11})m^2$	$1(10^{11})m^2$	$5(10^{10})m^2$
$\Delta\psi$ = 0.1215 (6.96°)	$\Delta\psi$ = 0.0991 (5.68°)	$\Delta\psi$ = 0.0701 (4.01°)	$\Delta\psi$ = 0.0496 (2.84°)
46.74° $\begin{bmatrix}5.4\\6.78\end{bmatrix}$	36.5° $\begin{bmatrix}3.84\\5.8\end{bmatrix}$	24.89° $\begin{bmatrix}2.44\\4.29\end{bmatrix}$	17.3° $\begin{bmatrix}1.6\\3.1\end{bmatrix}$
52.0° $\begin{bmatrix}5.94\\6.40\end{bmatrix}$	40.1° $\begin{bmatrix}4.026\\5.60\end{bmatrix}$	27.12° $\begin{bmatrix}2.48\\4.26\end{bmatrix}$	18.79° $\begin{bmatrix}1.65\\3.09\end{bmatrix}$
58.1° $\begin{bmatrix}6.76\\6.197\end{bmatrix}$	43.97° $\begin{bmatrix}4.25\\5.57\end{bmatrix}$	29.4 $\begin{bmatrix}2.53\\4.22\end{bmatrix}$	20.8° $\begin{bmatrix}1.67\\3.08\end{bmatrix}$
66.54° $\begin{bmatrix}8.19\\5.82\end{bmatrix}$	48.0° $\begin{bmatrix}4.547\\5.43\end{bmatrix}$	31.74° $\begin{bmatrix}2.59\\4.183\end{bmatrix}$	21.8° $\begin{bmatrix}1.69\\3.06\end{bmatrix}$
76.14° $\begin{bmatrix}11.8\\5.25\end{bmatrix}$	52.5° $\begin{bmatrix}4.94\\5.26\end{bmatrix}$	34.13° $\begin{bmatrix}2.66\\4.14\end{bmatrix}$	23.36° $\begin{bmatrix}1.71\\3.06\end{bmatrix}$
	57.47° $\begin{bmatrix}5.50\\5.06\end{bmatrix}$	36.6° $\begin{bmatrix}2.74\\4.09\end{bmatrix}$	24.9° $\begin{bmatrix}1.73\\3.03\end{bmatrix}$
	63.21° $\begin{bmatrix}6.38\\4.8\end{bmatrix}$	39.14 $\begin{bmatrix}2.8\\4.04\end{bmatrix}$	26.49° $\begin{bmatrix}1.75\\3.02\end{bmatrix}$
	70.427° $\begin{bmatrix}8.02\\4.49\end{bmatrix}$	41.78° $\begin{bmatrix}2.93\\3.98\end{bmatrix}$	28.09° $\begin{bmatrix}1.78\\3.0\end{bmatrix}$
		44.54° $\begin{bmatrix}3.06\\3.9\end{bmatrix}$	29.71° $\begin{bmatrix}1.8\\2.98\end{bmatrix}$
		47.42° $\begin{bmatrix}3.21\\3.84\end{bmatrix}$	31.38° $\begin{bmatrix}1.83\\2.96\end{bmatrix}$
		50.49° $\begin{bmatrix}3.4\\3.76\end{bmatrix}$	33.03° $\begin{bmatrix}1.86\\2.94\end{bmatrix}$
		53.8° $\begin{bmatrix}3.64\\3.67\end{bmatrix}$	34.7° $\begin{bmatrix}1.9\\2.92\end{bmatrix}$
		57.3° $\begin{bmatrix}3.94\\3.56\end{bmatrix}$	36.49° $\begin{bmatrix}1.94\\2.89\end{bmatrix}$
		61.24° $\begin{bmatrix}4.37\\3.44\end{bmatrix}$	38.28° $\begin{bmatrix}1.99\\2.86\end{bmatrix}$
		66.7° $\begin{bmatrix}5.0\\3.3\end{bmatrix}$	40.1° $\begin{bmatrix}2.04\\2.83\end{bmatrix}$

Table 5-1. Resolution Element Angular Coordinates (Continued)

A_{RE}

3(10¹¹)m²	2(10¹¹)m²	1(10¹¹)m²	5(10¹⁰)m²
Δθ = 0.1215 (6.96°)	Δθ = 0.0991 (5.68°)	Δθ = 0.701 (4.01°)	Δθ = 0.0496 (2.84°)
		71.2° [6.08 3.11]	41.90° [2.00 2.004]
			43.83° [2.156 2.77]
			45.94° [2.23 2.74]
			48.02° [2.31 2.7]
			50.19° [2.41 2.66]
			52.46° [2.52 2.6]
			54.86° [2.66 2.56]
			57.40° [2.83 2.51]
			60.14° [3.04 2.4]
			63.13° [3.32 2.38]
			66.47° [3.70 2.30]
			70.32° [4.28 2.21]

5.3.1 (Continued)

for θ_T = full angle exp (-2) transmitter beam width (irradiance). Using, for example, a square in circle for overlap from spot to spot, the square coverage area has a side

$$D_{SQ} = 0.707\, D_{SP} \quad . \tag{5-11d}$$

Then the total number of spots within a resolution element is given by

$$N_{SRE} = \frac{A_{RE}}{(D_{SQ})^2} \quad . \tag{5-11e}$$

Using D_{SP} = 30 km, Table 5-2 shows the number of spots within each resolution element area.

Table 5-2. Number of Illuminated Spots Per Resolution Elements for Square in Circle Overlap

A_{RE} (m²)	N_{SRE} (for D_{SP} = 30 km)
$3(10^{11})$	667
$2(10^{11})$	446
$1(10^{11})$	223
$5(10^{10})$	112

5.3.2 Temporal Relationships

A basic system requirement is that the total coverage area be communicated to within a time T_A, the area coverage time. This is accomplished by a spot scan. Therefore, if we define

M_D = Time to communicate to each spot, or
= Message duration, and

$t_{s\ell}$ = dead time between messages, or,
= time to scan to a new spot and develop the appropriate beam width, and

N_{TOTSP} = total number of spots within the coverage area, and finally,

t_w = source turn-on/warm-up time, then the total on time for a single source, during a given T_A interval, is given by

$$\boxed{T_{ON} = t_w + N_{TOTSP} M_D + (N_{TOTSP} - 1)t_{s\ell} = t_w + T_{TOT}} \tag{5-12a}$$

If the calculated $T_{TOT} > T_A$, and no adaptive techniques work to reduce it, then

$$\boxed{T_{ON} = t_w + T_A.} \tag{5-12b}$$

If the source has a pulse repetition rate given by PRF, then the total number of pulses used to communicate to the area during a given T_A is given by

$$\boxed{N_{PL} = (T_{ON})(PRF).} \tag{5-13a}$$

Naturally there should be a check that

$$(N_{TOTSP} - 1)\, t_{s\ell} + N_{TOTSP} M_D \leq T_A, \tag{5-13b}$$

or the system will not meet the requirement.

5.3.3 Message

The fundamental message length to be delivered over the time T_A to the coverage area is defined as M_{Lo}, with units "bits." In some cases, the total number of bits that must be communicated to each spot exceeds M_{Lo} because of the quality of service, jamming, spoofing, or practical hardware considerations. We therefore define

$$\boxed{M_L = M_{Lo} + M_{OV}} \tag{5-15}$$

for M_L = total message length (bits), and M_{OV} = overhead bits added to each message.

One key requirement is the number of missed messages per year, defined as N_M. Evidently the total number of messages per year is given by

$$\frac{\#\text{ Messages}}{\text{Year}} = \frac{\#\text{ Seconds per year}}{T_A} = \frac{3.15576\ (10^7)}{T_A} .$$

Then if N_M is the number of missed messages per year, the probability of a missed message is given by

$$\boxed{P_M = \frac{N_M\ T_A}{3.15576\ (10^7)}} \tag{5-16}$$

5.3.4 Modulation/Demodulation

There are three system requirements which interact with/determine the modulation/demodulation approach:

N_M = # of missed messages per year per boat;

N_j = # of jammed messages per year per boat;

N_{SP} = # of spoofed messages per year per boat.

This section considers these requirements in terms of the M'ary modulation format and various demodulation approaches.

5.3.4.1 Modulation

The PPM (pulse position modulation) format is used here to minimize required optical (average) power and to maximize the data transfer rate for a given source pulse repetition rate.

The building blocks of the format are slots and frames, as shown in Figure 5-6. Defining t_s = slot width, and
ℓ = # of bits/pulse,
then if 2^ℓ resolvable slots are included in one frame, the location of a pulse in any one of these slots will denote the ℓ bits.
Therefore, frame width = $(2^\ell)\ t_s$ seconds.

If in addition we define t_ℓ = dead time between frames,
then a message containing a total of M_L (bits) will have a message duration M_D (seconds) given by

$$M_D = \left(\frac{M_L}{\ell}\right)\left(\frac{2^\ell\ t_s}{1}\right) + \left(\frac{M_L}{\ell} - 1\right)\ t_f,$$

or,

$$\boxed{M_D = \left(\frac{M_L 2^\ell t_s}{\ell}\right) + \left(\frac{M_L}{\ell} - 1\right)\ t_f.} \qquad (5\text{-}17)$$

The message length is determined partially by the demodulation technique, since the format and the requirements (N_M, N_{ji} and N_{SPi}) determine the required number of overhead bits to be added to M_{Lo}, the fundamental message length.

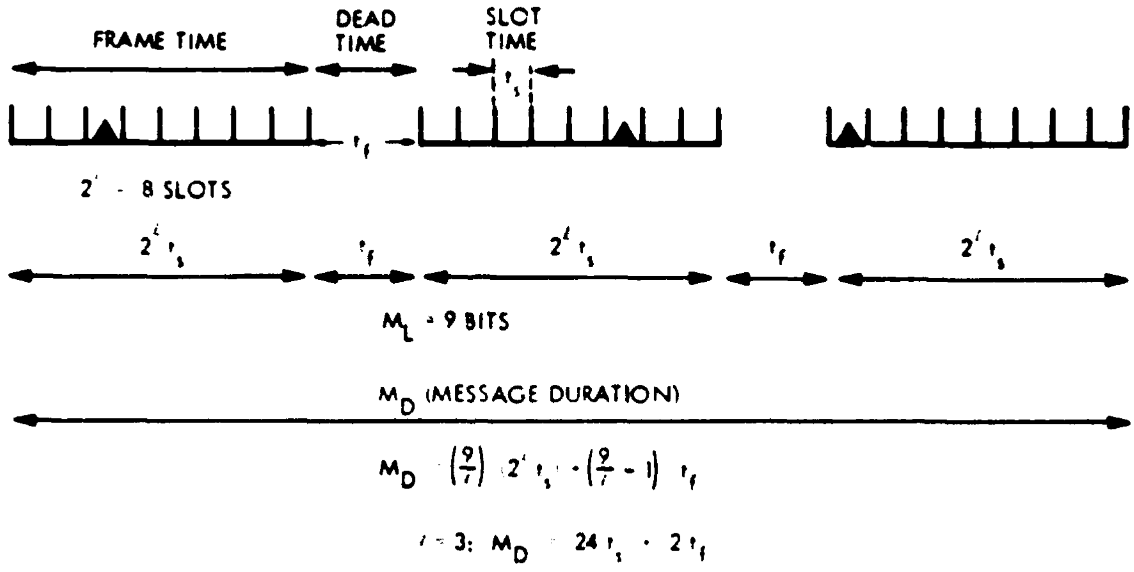

Figure 5-6. i=3, M_L=9 PPM Example

5.3.4.2 Demodulation

Given the fundamental message length, M_{Lo}, the requirements (N_M, N_j, N_{SP}) and the demodulation technique, the required signal to noise ratio per pulse and the number of overhead bits are determined.

5.3.4.2.1 Threshold Detection

The first demodulation technique considered is threshold detection, i.e., the pulse will be said to occur at a given time (within a given slot) if the received power exceeds a preset level, as shown in Figure 5-7.

Errors occur when the noise exceeds this threshold or the signal + noise falls below this threshold.

We define P_E = bit error probability:

and P_p = pulse error probability;

so that $P_E = \frac{P_p}{2}$ (5-18)

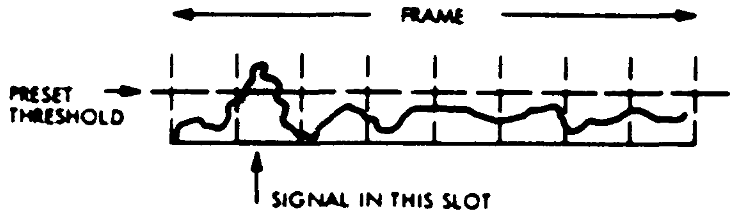

Figure 5-7. Threshold Demodulation for PPM Format

5.3.4.2.1 (Continued)

The probability of a pulse error is composed of the probability of a missing pulse, P_m , and the probability (P_N) that at least one of the (2^{ℓ}-1) time slots contain a noise spike, so that

$$P_p = P_m + P_N. \quad (5\text{-}19)$$

Since there are 2^{ℓ}-1 opportunities for a noise spike, the allowable single pulse probability of false alarm, P_{FA}, is

$$P_{FA} = \frac{P_N}{2^{\ell}-1} . \quad (5\text{-}20)$$

We arbitrarily assume

$$P_m = \frac{P_p}{2} \text{ and } P_N = \frac{P_p}{2} . \quad (5\text{-}21)$$

which means (5-21)

$$P_m = \frac{P_p}{2} = P_E \quad .$$

5.3.4.2.1 (Continued)

and $$P_{FA} = \frac{P_N}{2^{\ell}-1} = \frac{P_E}{(2^{\ell}-1)} \quad . \tag{5-22}$$

From gaussian detection theory[1], *

$$P_{FA} = \frac{1}{2.3} \quad \exp - \left(\frac{I_t^2}{2I_n^2} \right) \tag{5-23}$$

and $$P_m = \frac{1}{2.3} \quad \exp - \left(\frac{(I-I_t)^2}{2I_n^2} \right) \tag{5-24}$$

for I = Peak signal current = $(ne/h\nu)\ P_R$,

I_n = rms noise current = $(ne/h\nu)\ (NEP_{TOT})$,

and I_t = threshold current.

We can therefore rewrite these equations as

$$\frac{I_t}{I_n} = (TNR) = \left[-2 \ln\ (2.3\ P_{FA})\right]^{1/2} \quad . \tag{5-25}$$

and $$\frac{I}{I_n} = \left(\frac{S}{N}\right) = \left[-2 \ln \left(2.3\ P_E\right)\right]^{1/2} + \left[-2 \ln \left(\frac{2.3\ P_E}{(2^{\ell}-1)}\right)\right]^{1/2} . \tag{5-26}$$

Recall equation (5-16)

$$P_m = \frac{N_m \quad T_A}{3.15576\ (10^7)} \quad .$$

* Due to large background levels, the Gaussian regime applies almost always in the OSCAR scenario.

5.3.4.2.1 (Continued)

for N_M = # of missed messages per year,

T_A = time to deliver each message to the coverage area,

P_M = probability of a missed message.

If we take the probability of a missed pulse to be the same as the probability of a missed message, then

$$P_M = \frac{P_p}{2} = \frac{N_M \; T_A}{3.15576 \; (10^7)} . \tag{5-27}$$

and re-using

$$P_{FA} = \frac{P_p}{2(2^\ell - 1)} = \frac{N_M \; T_A}{2(2^\ell - 1) \; 3.15576 \; (10^7)} , \tag{5-28}$$

and

$$P_\varepsilon = \frac{P_p}{2} = \frac{N_M \; T_A}{3.15576 \; (10^7)} \tag{5-29}$$

then the threshold-to-noise ratio becomes

$$\boxed{TNR = \left[-2 \ln \left(\frac{\sqrt{3} \quad N_M \; T_A}{(2^\ell - 1) \; 3.15576(10^7)}\right)\right]^{1/2}} \tag{5-30}$$

while the signal-to-noise ratio becomes

$$\boxed{\frac{S}{N} = \left[-2 \ln \left(\frac{2 \sqrt{3} \quad N_M \; T_A}{[3.15576 \; (10^7)]}\right)\right]^{1/2} + \left[-2 \ln \left(\frac{2 \sqrt{3} \quad N_M \; T_A}{(2^\ell - 1) \; (3.15576(10^7))}\right)\right]^{1/2}} \tag{5-31}$$

These expressions yield the required single pulse (TNR) and S/N in terms of the requirements, N_M and T_A, and a parameter of the modulation format, ℓ.

In considering the jamming (N_J) and spoofing (N_{SP}) requirements and their effects on the system parameters, we start with the following assumptions:

5.3.4.2.1 (Continued)

(1) Frame times, slot times, average PRF and scanning patterns are all unknown to the Spoofer/Jammer;

(2) "g" times as many spoof/jam pulses occur on the average in any given time period as do signal pulses;

(3) Spoof/jam pulses are of amplitude equivalent to the signal pulses, and will cross the threshold;

(4) Submarine position is unknown to the spoofer/jammer;

(5) The scanning of the spoofer/jammer is random.

In effect, then, the submarine is fixed in space during the scanning time, and the received spoof/jam pulses will occur randomly in time because of both random scanning and random timing.

The number of signal pulses received in every period T_A will be

$$N_{si} = \frac{M_L}{i} , \tag{5-32}$$

while the number of spoof/jam pulses will be

$$_{SP}N_{si} = \frac{g\ M_L}{i} . \tag{5-33}$$

Then the probability of a spoof/jam pulse occuring in any particular time slot of width t_s within the time T_A is

$$P_1 = 1 - \left(1 - \frac{t_s}{T_A}\right)^{_{SP}N_{si}} \approx \left(\frac{g\ M_L}{i}\right)\left(\frac{t_s}{T_A}\right) , \tag{5-34}$$

for $\frac{t_s}{T_A} << 1$.

5.3.4.2.1 (Continued)

To spoof the receiver we will assume that one and only one pulse will occur in each of the M_L/ℓ frames. Then the probability of one and only one pulse occurring in a frame of 2^{ℓ} slots is

$$2^{\ell}\, P_1\, (1-P_1)^{2^{\ell}-1},$$

and the joint probability that M_L/ℓ frames are satisfied is

$$P_{SP} = \left\{ 2^{\ell}\, P_1\, (1-P_1)^{2^{\ell}-1} \right\}^{M_L/\ell} . \tag{5-35}$$

For the message duration given by M_D in (5-17), the number of message durations per year are given by

$$\frac{3.15576\ (10^7)}{M_D} ,$$

so that the number of successful spoofing events per year is

$$N_{SP} = P_{SP}\ \frac{3.15576\ (10^7)}{M_D} . \tag{5-36}$$

Using (5-17), (5-34) and (5-35),

$$\boxed{N_{SP} = \left\{ 2^{\ell} \left(\frac{g\, M_L}{\ell}\right)\left(\frac{t_s}{T_A}\right) \left[1 - \left(\frac{g\, M_L}{\ell}\right)\left(\frac{t_s}{T_A}\right)\right]^{2^{\ell}-1} \right\}^{M_L/\ell} [3.15576\ (10^7)]\ X \left\{\left(\frac{M_L\, 2^{\ell} t_s}{\ell}\right) + t_f \left(\frac{M_L}{\ell} - 1\right)\right\}^{-1}} \tag{5-37}$$

5.3.4.2.1 (Continued)

This expression is used to calculate N_{SP} as a function of the requirements (g, M_L, T_A), hardware parameters (t_s, t_p) and modulation format (ℓ). The result is to be compared with the inputted requirement for spoofing:

$$N_{SPi} \leq N_{SP}. \tag{5-38}$$

Jamming is defined here as either inserting one extra pulse in any signal frame, or inserting at least one pulse in a frame immediately preceding or following the signal frames.

The probability of at least one extra pulse in the M_L/ℓ frames is

$$P_{J1} = 1 - \left[(1 - P_1)^{2^{\ell}-1}\right]^{\frac{M_L}{\ell}}, \tag{5-39}$$

while the probability that at least one pulse exists in either adjacent frame is

$$P_{J2} = 1 - \left[(1 - P_1)^{2^{\ell}}\right]^{2}. \tag{5-40}$$

The total jamming probability is then

$$P_J = 1 - (1 - P_{J1})(1 - P_{J2})$$

$$= 1 - [1 - P_1]^{(2^{\ell}-1)\frac{M_L}{\ell} + 2^{\ell+1}}. \tag{5-41}$$

Since these are $\frac{3.15576\,(10^7)}{T_A}$ messages received per year per boat, the number of jammed messages per boat is given by

$$N_J = P_J \frac{3.15576\,(10^7)}{T_A}. \tag{5-42}$$

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5.3.4.2.1 (Continued)

Using (5-34) and (5-41),

$$\boxed{N_J = \left\{ 1 - \left[1 - \left(\frac{g\, M_L}{\ell} \right) \left(\frac{t_s}{T_A} \right) \right]^{\left\{ (2^{\ell}-1) \frac{M_L}{\ell} + 2^{i}+1 \right\}} \right\} \frac{3.15576\ (10^7)}{T_A}\ .} \qquad (5\text{-}43)$$

This expression is used to calculate the number of jammed messages per boat per year, N_j, as a function of the other requirements (g, M_L, T_A), a hardware parameter (t_s) and a property of the modulation format (ℓ). The result is to be compared with the inputted requirements for jamming:

$$N_{ji} \leq N_j. \qquad (5\text{-}44a)$$

Note that no additional bits were added to obtain suitable operation, and so for threshold demodulation,

$$\boxed{M_L = M_{Lo}} \qquad (5\text{-}44b)$$

5.3.4.2.2 Time-of-Peak Detection

The second demodulation technique considered is time-of-peak detection, i.e., the pulse is determined to occur at that time within the frame at which the maximum value of received energy occurs, as shown in Figure 5-8. This determination is made following a filter matched to the pulse width.

The probability of error is now taken as the probability of at least one noise peak exceeding the signal peak and in an incorrect time slot. This is done using the bound on this probability[2],

$$P(x) \leq \frac{\gamma - 1}{\sqrt{2 \pi (I^1/I_n)^2}} \exp - \left[2 \left(\frac{I}{I_n} \right)^{2} \right]. \qquad (5\text{-}45)$$

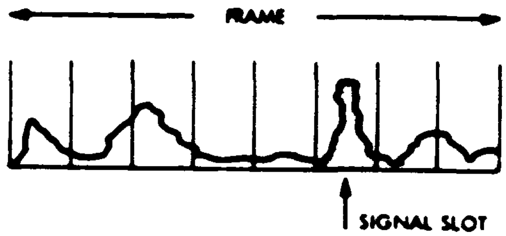

Figure 5-8. Time-of-Peak Demodulation for PPM Format

5.3.4.2.2 (Continued)

for y = number of slots in the frame = 2^{ℓ}

$$\left(\frac{I}{I_n}\right)^2 = \left(\frac{S}{N}\right)^2 ,$$

x = the event corresponding to one peak exceeding the signal level at a given S/N.

Therefore, $P(x) = P_p = P_E \; \frac{2\,(2^{\ell})}{(2^{\ell}-1)}$

and $\quad P_E \leq \frac{2^{\ell}-1}{2\sqrt{2\pi}\; S/N} \quad \exp - \left\{ \frac{1}{2}\left(\frac{S}{N}\right)^2 \right\} .$

and using (5-29) again,

$$\frac{N_M\, T_A}{3.15576\,(10^7)} \leq \frac{2^{\ell}-1}{2\sqrt{2\pi}\;(S/N)} \exp - \left[\frac{1}{2}\left(\frac{S}{N}\right)^2 \right] . \qquad (5\text{-}46)$$

This equation cannot be inverted to yield the S/N required to satisfy a given $N_M T_A$ requirement for a given modulation format, ℓ. Instead, for the given ℓ and $N_M T_A$, values of (S/N) are inserted until the equation is satisfied, and that value is

5.3.4.2.2 (Continued)

taken as the required (S/N). S/N = 5 is the lowest value considered, and it is incremented in steps of 0.1 until (5-46) is satisfied for the value of ℓ selected.

The time-of-peak demodulation technique provides an extreme problem for the signal processor, since every frame will have a peak and therefore every group of frames of appropriate length will have to be processed to search for a signal.

To relieve this problem and meet the N_m (# of missed messages per year per boat) requirement, we consider the addition of w extra frames, each containing a pulse in its own preselected slot. If we then state that the receipt of a false message (due to ambient noise sources) is equivalent to the loss of a true message, we may proceed as follows:

If the signature pulse may be in any one of the 2^ℓ slots of a given frame, and w signature pulses (in w frames) are used, then the probability that the total signature will be duplicated is approximately given by

$$P_{FS} = \frac{1}{(2^\ell)^w} = \frac{1}{2^{\ell w}}. \tag{5-47}$$

Since the first frame of a false signature may be any frame in a year, the expected number of false signatures per year is the same as the number of missed messages per year, or,

$$N_M = P_{FS} \left(\frac{3.15576\ (10^7)}{2^\ell\ t_s} \right) = \frac{3.15576\ (10^7)}{t_s\ 2^{\ell\ (w+1)}}. \tag{5-48}$$

Solving for w we find

$$2^{\ell(w+1)} = \frac{3.15576\ (10^7)}{t_s\ N_M},$$

or,

$$\boxed{w = \frac{1}{\ell} \left\{ 24.91 - 1.44 \ln (t_s N_M) \right\} - 1.}$$

5.3.4.2.2 (Continued)

with the provision that the result of (5-49) is always rounded off to the next highest integer if it is non-integer, since the # of additional signal frames must be an integer.

This procedure results in a number of overhead bits per message,

$$\boxed{M_{OV} = w\ell,} \tag{5-50}$$

and a total message length

$$\boxed{M_L = M_{L0} + w\ell.} \tag{5-51}$$

In considering the jamming (N_j) and spoofing (N_{SP}) requirements, the same 5 assumptions as in Section 5.3.4.2.1 are again made. In particular, "g" times as many spoof/jam pulses occur on the average in any given time period as do signal pulses.

Consider spoofing:

The number of signal pulses received during area coverage time T_A is

$$N_{si} = \frac{M_L}{\ell}, \tag{5-52}$$

while the average number of threat pulses during the same time is

$${}_{SP}N_{si} = \frac{g\,M_L}{\ell}. \tag{5-53}$$

Then the probability that one threat pulse will occupy any particular slot (of width t_s) within the time T_A is

$$P_1 = 1 - \left(1 - \frac{t_s}{T_A}\right)^{{}_{SP}N_{si}} = \frac{g t_s M_L}{\ell\, T_A}, \tag{5-54}$$

for $t_s \ll T_A$.

5.3.4.2.2 (Continued)

To spoof a message using the w signature pulse approach requires that all w pulse positions be duplicated. Therefore, the probability of spoofing is

$$P_{SP} = (P_1)^w = \left(\frac{g\ t_s\ M_L}{\ell\ T_A}\right)^w . \tag{5-55}$$

Since the message duration is

$$M_D = \left(\frac{M_L 2^{\ell} t_s}{\ell}\right) + \left(\frac{M_L}{\ell} - 1\right)\ t_f , \tag{5-56}$$

for t_f = interframe dead time,

and there are $\dfrac{3.15576\ (10^7)}{M_D}$ opportunities for messages per year,

then the number of spoof events per year are

$$N_{SP} = P_{SP}\ \frac{3.15576\ (10^7)}{M_D} ,$$

or,

$$\boxed{N_{SP} = 3.15576\ (10^7)\ \left(\frac{g\ t_s\ M_L}{\ell\ T_A}\right)^w \left\{\frac{1}{\left(\frac{M_L}{\ell}\ t_s\ 2^{\ell}\right) + \left(\frac{M_L}{\ell} - 1\right)\ t_f}\right\}\ .} \tag{5-57}$$

Once w is determined by (5-49), (5-57) is evaluated to determine if the spoofing requirement is met, so that (5-57) is compared to the inputted spoofing requirement:

$$N_{SPi} \leq N_{SP} . \tag{5-58}$$

With regard to jamming, we assume initially that jamming occurs whenever a threat pulse falls within a signature frame in any unoccupied slot, since then the

5.3.4.2.2 (Continued)

signature will not be recognized. Since there are $2^\ell - 1$ unoccupied slots within each signature frame, the probability of jamming is

$$P_J = 1 - (1 - P_1)^{w(2^\ell - 1)} \approx w\,(2^\ell - 1)\,\frac{g\,t_s\,M_L}{\ell\,T_A}, \tag{5-59}$$

again for $t_s \ll T_A$.

Since there are $\frac{3.15576\,(10^7)}{T_A}$ messages sent per year, the number of jammed messages is

$$\boxed{N_j = 3.15576\,(10^7)\,\frac{w\,(2^\ell - 1)\,g\,t_s\,M_L}{\ell\,T_A}} . \tag{5-60}$$

Again, after evaluation the comparison is made

$$N_{ji} \gtrless N_j. \tag{5-61}$$

However, many values of the parameters exist for which $N_j < N_{ji}$, for all other requirements easily met. We therefore consider an alternative post-detection processing scheme, which will accept a frame with two peaks, one of which is in the correct slot, as a valid signature frame. Then to jam the link, two threat pulses would have to occur in the signature frames.

Since the probability that a single threat pulse occurs within a given frame in an unoccupied slot is

$$P_F = 1 - (1 - P_1)^{2^\ell - 1} \approx (2^\ell - 1)\,P_1, \tag{5-62a}$$

(for $P_1 \ll 1$, true for $t_s \ll T_A$). Then the probability that two threat pulses occur in a given frame is

$$P_{2F} = (P_p)^2 = [1 - (1 - P_1)^{2^\ell - 1}]^2 \approx (2^\ell - 1)^2\,P_1{}^2. \tag{5-62b}$$

5.3.4.2.2 (Continued)

Then the jamming probability is the probability that two pulses occur in any of w frames, so that

$$P'_J = 1 - (1 - P_{2F})^w = wP_{2F} = w(2^\ell - 1)^2 \; P_1 2$$

or, $$P'_J = w(2^\ell - 1)^2 \left(\frac{g \; t_s \; M_L}{\ell \; T_A}\right)^2 \; . \qquad (5\text{-}63)$$

and $$\boxed{N'_J = 3.15576 \; (10^7) \; \frac{w(2^\ell - 1)^2}{T_A} \; \left(\frac{g \; t_s \; M_L}{\ell \; T_A}\right)^2 \; .} \qquad (5\text{-}64a)$$

and the comparison equation is

$$N_{ji} \geq N'_j \; . \qquad (5\text{-}64b)$$

In running this program, then, the post-detection processing must be specified before it can be determined if the jamming requirement is satisfied.

References for Section 5.3.4

1. RCA Electro-Optics Handbook, Section 8, RCA - 1968

2. J. M. Wozencraft and I. M. Jacobs, "Principles of Communication Engineering," John Wiley and Sons, 1965, p 629.

5.3.5 Scanning Relationships

The area to be covered is illuminated by spots of relatively small diameter. Each spot is illuminated for a length of time given by the message duration (M_D) of equation (5-17), and then the transmitter is redirected to a new spot. If we define this slewing time as $t_{s\ell}$, then the total time devoted to each spot may be taken as,

$$T_{SP} = M_D + t_{s\ell}. \qquad (5\text{-}65)$$

To determine the total time to scan the entire area of responsibility, we define

A_{SP} = area of spot

and A_{SC} = area of useful coverage within the illuminated spot.

As a baseline we take the square in circle pattern defined in Figure 5-9a. The effective area covered by the inside square is given by

$$A_{sc} = \epsilon^2 D^2_{sp} = D^2_{sq}$$

where:

D_{sp} = spot diameter,

D_{sq} = square side,

ϵ = overlap factor, defined by

$D_{sq} = \epsilon D_{sp}$.

Since $A_{sp} = \frac{\pi}{4} D_{sp}^2$

$$\boxed{A_{scMIN} = \frac{4\epsilon^2}{\pi} A_{sp} = \epsilon^2 D^2_{spMIN}} \qquad (5\text{-}68)$$

and $(4\epsilon^2/\pi)$ is the general efficiency factor of the scan pattern. For $\epsilon = 0.707$, this efficiency factor = $(2/\pi) = 0.637$, which is the highest possible for any square inside a circle.

5.3.5 (Continued)

There is a finite probability that the motion of a submarine may allow it to escape communication (connectivity failure) if its initial position and velocity value are unfavorably related to the scan pattern. We will here estimate the probability of these positions and velocity vectors occurring if the submarine is randomly positioned relative to the scan pattern.

The baseline "square-in-a-circle" scan is assumed and the squares are offset in succeeding lines. The worst case for timing is assumed: the adjacent spots are visited with the maximum elapsed time. It is also assumed that the submarine velocity magnitude is constant and that the velocity vector direction is constant during the intermessage times.

The square in a circle pattern is as shown in Figure 5-9.

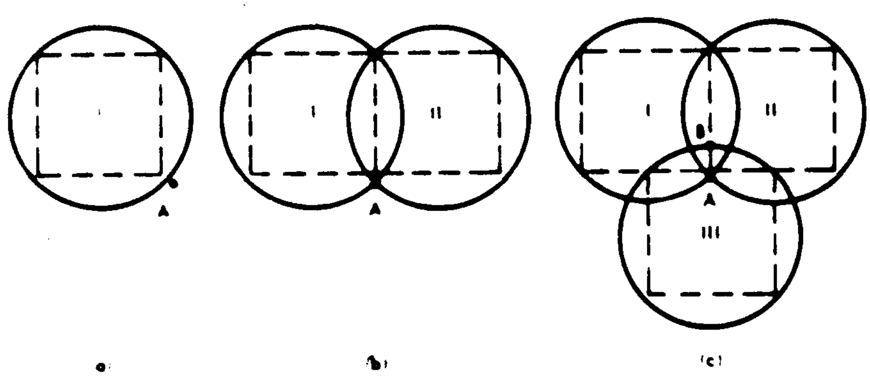

Figure 5-9. Square-in-Circle Overlap Scan Pattern

We will concentrate on area II' which receives the message during the last spot of revisit time with areas I and II being first spots illuminated.

If a submarine is in area III during the first spot time, and moves out of circle 3 during revisit time, it will escape communication.

5.3.5 (Continued)

Because of the symmetry of the problem, we will consider only one eighth of the square as shown in Figure 5-9d.

The square side is D_{SQ} and the circle radius is $\frac{D_{sp}}{2}$. Thus $D_{SQ} = \frac{\sqrt{2}}{2} D_{sp}$.

If vT_A is the distance the submarine moves during revisit time, there is an area, A, within which the submarine cannot escape communication. There is also an area B within which the submarine will have been communicated to during the first frame.

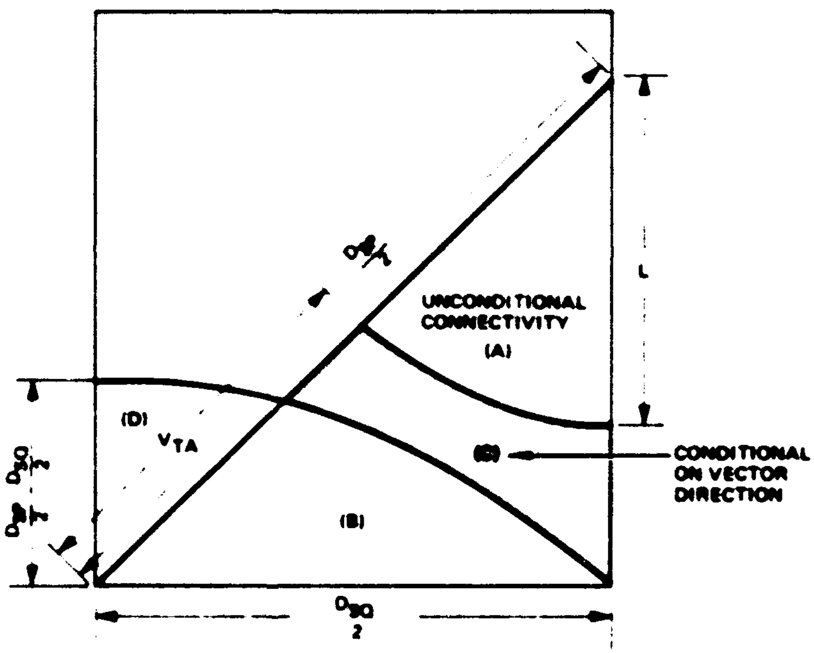

Figure 5-9d. Escape Geometry

The area C is an area within which the submarine may escape if the velocity direction is within bounds.

5.3.5 (Continued)

It is difficult to write an analytical expression for area C but it can be approximated by the followong approach:

$$\text{Area A} = \frac{\pi\left(D_{sp/2} - vT_A\right)^2}{8}$$

$$\text{Area (B+D)} = \frac{\pi R^2 - S^2}{8} = \frac{\pi R^2 - 2R^2}{8} = R^2\frac{(\pi - 2)}{8} = \frac{\pi\left(\frac{D_{sp}}{2}\right)^2 - D_{SQ}}{8} = \frac{\left(\frac{D_{sp}}{2}\right)^2(\pi - 2)}{8}$$

$$\text{Area D} = \frac{\left(R - \frac{S}{2}\right)^2}{2} = \frac{R^2\left(1 - \frac{\sqrt{2}}{2}\right)^2}{2} = \frac{\left(\frac{D_{sp}}{2} - \frac{D_{SQ}}{2}\right)^2}{2} = \frac{\left(\frac{D_{sp}}{2}\right)^2\left(1 - \frac{\sqrt{2}}{2}\right)^2}{2}$$

$$\text{Area B} = \left(\frac{D_{sp}}{2}\right)\left[\frac{\pi}{8} - \frac{1}{4} - \frac{1}{2} + \frac{\sqrt{2}}{2} - \frac{1}{4}\right] = 0.0998\left(\frac{D_{sp}}{2}\right)^2$$

$$\text{Area A+B+C} = \frac{S^2}{8} = \frac{R^2}{4} = \frac{D_{SQ}{}^2}{8} = \frac{1}{4}\left(\frac{D_{sp}}{2}\right)^2$$

The probability of conditional escape is:

$$P_{CE} = \frac{C}{(A+B+C)} = \frac{(A+B+C)-A-B}{(A+B+C)} = 1.-0.171 - \frac{\pi}{2}\left(1 - \frac{vT_A}{\left(\frac{D_{sp}}{2}\right)}\right)^2$$

Note that the probability can never be less than zero, therefore:

$$\frac{vT_A}{\frac{D_{sp}}{2}} \geq 0.274 \qquad \text{for conditional escape.}$$

Therefore for the condition

$$D_{sp} \geq 7.3\ vT_A \quad \text{there will be no connectivity failure.}$$

5.3.5 (Continued)

However, this is unnecessarily restrictive. Consider a particular case with the following assumed values:

1. Spot size (minimum) D_{SQ} = 20 Km, $\frac{D_{sp}}{\sqrt{2}}$ = 14.1 Km

2. Submarine velocity x time = 6 Km

Therefore $\frac{vT}{D_{sp}}$ = 0.424 which exceeds the limit above. This area is the darker shaded area in Figure 5-9e.

This area is estimated graphically as two small triangles with areas of 7 squares and 3 squares, respectively, where the total area (A+B+C) is 128 squares

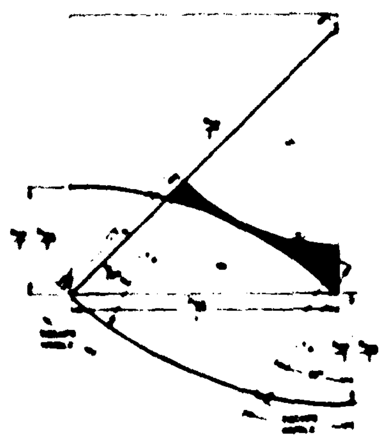

Figure 5-9e. Escape Geometry

The direction of possible escape from the larger triangle is any angle less than an estimated 35° from the radius line. Therefore, assuming uniform probability of direction, the probability of escape direction is

$$\frac{35°}{180°} = 0.1944$$

From the smaller triangle the escape direction must be less than 20 from radius vectors which leads to a probability of 0.111.

Therefore the overall probability of escape with these conditions is:

$$P = \frac{7}{128} \times 0.1944 + 3 \times 0.111 = 0.0106 \times 0026 = 1.3\%$$

5.3.5 (Continued)

Note that if $vT_A \leq$ 4km, there is no escape. Thus, if the time is random, there is only a 1/3 probability that vT is greater than 4 for the particular velocity.

Therefore the probability of escape is less than

$P_E \leq 0.4\%$

especially considering the narrower escape angles which have not been included in the approximation and that other worst-case assumptions have been made.

It should also be noted that on a purely statistical basis one would estimate that the probability of two consecutive connectivity failures would be $(.004)^2 = 1.6 \times 10^{-5}$. However, by studying the geometry, one realizes that if the direction is not abruptly changed, the submarine is in an unconditional area at the start of the second period and will not escape communication.

Therefore, it is concluded that the probability of connectivity failure is considered negligibly small if

$$\boxed{D_{SP} \geq 4.7\ vT_A.}$$

For the OSCAR requirements, this condition is nearly always met, so we shall not consider this as a limit in the DCM analysis. (Section 4.3 of Volume 4 discusses this point further.)

Returning now to our basic discussion of scanning, and the number of spots per resolution element, recall A_{RE} = area of resolution element. Thus the number of illuminated spots within a resolution element is given by

$$\boxed{N_{SREMAX} = \frac{A_{RE}}{A_{scMIN}}.} \qquad (5\text{-}69)$$

If there are $N_{TOT\ RE}$ resolution elements within the area of responsibility of the satellite, then the total number of spots (assuming equal beam diameters throughout) is given by

$$\boxed{N_{TOT\ sp} = (N_{TOT\ RE})\ (N_{SRE})} \qquad (5\text{-}70)$$

5.3.5 (Continued)

and the total time required to cover the entire area of responsibility is

$$T_{TOT} = (N_{TOT\ sp})\ (T_{sp}) - t_{s\ell} \tag{5-71a}$$

$$\boxed{T_{TOT} = (N_{TOT\ sp})\ (M_D) + (N_{TOT\ sp} - 1)\ t_{s\ell}.} \tag{5-71b}$$

If $T_{TOT} > T_A$, then another terminal located on the satellite is required. We shall discuss this further in Section 5.3.7 on Adaptive Scanning.

For an elliptical spot, the area is given by

$$A_{sp} = \frac{\pi}{4} D_{sp}\ D_{sp} (\cos \theta_s)^q \tag{5-73}$$

for θ_s = signal zenith angle

q = factor between 0 and 1 related to the satellite transmitter's ability to correct for the zenith angle spreading.

From the properties of ellipses, any rectangle within an ellipse which touches all sides has the area

$$\boxed{A_{RCTijMIN} = D_{spMIN}\ D_{spMIN} (\cos \theta_{sij})^q\ \epsilon\ (1 - \epsilon^2)^{1/2}} \tag{5-74}$$

which leads to the area efficiency coverage factor

$$\frac{A_{RCT}}{A_{sp}} = \frac{4}{\pi}\ \epsilon (1 - \epsilon^2)^{1/2} \tag{5-75}$$

and the same condition on t_{ARV} as (5-67) if the ellipses are overlapped as the circles are in Figure 5-9. This efficiency factor is maximized for $\epsilon = 0.707$, just as for the square in the circle approach, and again = 0.637.

5.3.5 (Continued)

The number of spots per resolution element would now be

$$\boxed{N_{SREij} = \frac{A_{RE}}{A_{RCTij}}} \tag{5-76}$$

and (5-70) and (5-71) are then useable for the new value of N_{SREij} when summed over ij.

The final key parameter of the scan pattern is the allowable minimum size of D_{sp} determined by satellite stability. This diameter is related to the satellite range and beam divergence by

$$D_{sp} = R\theta_T \tag{5-77}$$

for the assumed small angles involved here.

θ_T, in turn, must be greater than a minimum determined by

(1) The satellite's induced pointing jitter during a single message duration, which we characterize by its rms value θ_{TS}.

(2) The satellite long term angular drift, so that a spot position adjacent to a previously illuminated spot is precisely located. This effect is characterized by its rms value θ_{TDR}.

Negligible pointing induced signal loss is encountered if

$$\theta_{TMIN} = 10 \left(\theta_{TS}^{\ 2} + \theta_{TDR}^{\ 2}\right)^{1/2}, \tag{5-78}$$

which implies

$$\boxed{D_{spMIN} = 10\, R_{ijMAX} \left(\theta_{ts}^{\ 2} + \theta_{TDR}^{\ 2}\right)^{1/2}} \tag{5-79}$$

This point will be further discussed in Section 5.3.7 on Adaptive Scanning.

5.3.6 Receiver and Source

Some particular aspects of the laser transmitter and receiver must be modelled in order to provide a full downlink communications model.

5.3.6.1 Receiver

We need to derive the in-water angle, ξ, between the optical axis of the receiver and the signal beam, the sun, the moon, and the local vertical, respectively.

We first consider the signal beam. The input to the model is the latitude (α_s), longitude (β_s) and altitude (R_s) of the satellite, and the latitude (α_{Aj}) and longitude (β_{Aj}) of the receiver. From these, in Section 5.3.1 we derived the range from satellite to receiver [R, equation (5-2)], and the signal zenith angle into the water [θ_s, equation (5-5)]. Since ξ_{SR} is the in-water angle between receiver optical axis and signal principal direction, we must transform the input information into the local coordinate system centered on the receiver and oriented to local vertical. It is also useful to align an axis with the local longitude.

We therefore perform the following coordinate transformations (cf Figure 5-10):

1. (x_1, y_1, z_1) is the earth centered system
2. (x_2, y_2, z_2) is the system whose origin is at the receiver, but whose three axes are parallel to the earth-centered axis.
3. (x_3, y_3, z_3) is a system resulting from the rotation of the (x_2, y_2, z_2) system about the z_2 axis by an angle β_j.
4. (x_4, y_4, z_4) is a system resulting from the rotation of the (x_3, y_3, z_3) system about the y_3 axis by an angle $(\frac{\pi}{2} - \alpha_j)$, resulting in z_4 along the local vertical and x_4 along the direction of constant longitude.

In the (x_1, y_1, z_1) system, x_E and x_s are given by the equation immediately following equation (5-1) [equation (5-1a) through (5-1f)]. For the sateilite, then, the transformation of its coordinates into the (x_2, y_2, z_2) system is given by

$$x_2 = x_s - x_E; \tag{5-80a}$$

$$y_2 = y_s - y_E; \tag{5-80b}$$

$$z_2 = z_s - z_E. \tag{5-80c}$$

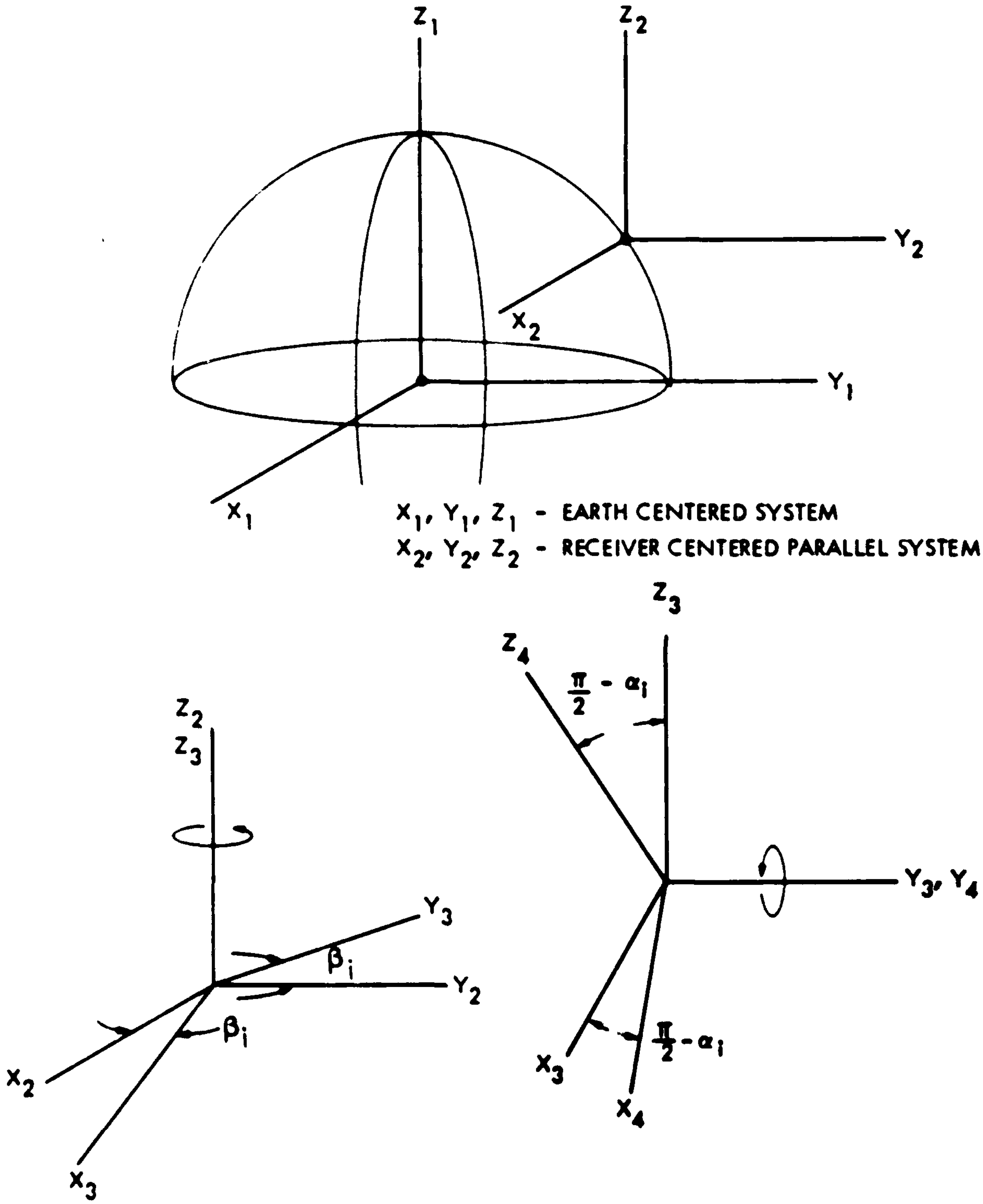

Figure 5-10. OSCAR Coordinate Transformation

5.3.6.1 (Continued)

Rotation about the z_2 axis by an angle β_j results in the transformation equation,

$$x_3 = x_2 \cos \beta_j + y_2 \sin \beta_j; \tag{5-81a}$$

$$y_3 = y_2 \cos \beta_j - x_2 \sin \beta_j; \tag{5-81b}$$

$$z_3 = z_2. \tag{5-81c}$$

Finally, rotation about the x_3 axis by the angle $(\frac{\pi}{2} - \alpha_i)$ results in the transformation equations

$$x_4 = x_3 \sin \alpha_i - Z_3 \cos \alpha_i; \tag{5-82a}$$

$$y_4 = y_3; \tag{5-82b}$$

$$z_4 = z_3 \sin \alpha_i + y_3 \cos \alpha_i. \tag{5-82c}$$

The signal zenith angle in the last coordinate system is given by

$$\theta_s = \cos^{-1} \left\{ \frac{z_4}{[x_4^2 + y_4^2 + z_4^2]^{1/2}} \right\} \tag{5-83a}$$

which is equivalent to the result in equation (5-5).

The signal azimuth (relative to β_j because of the coordinate transformation) is given by

$$\boxed{\theta_{sAij} = \tan^{-1} \left(\frac{y_4}{x_4} \right) = \tan^{-1} \left\{ \frac{(y_s - y_E) \cos \beta_j - (x_s - x_E) \sin \beta_j}{\left[(x_s - x_E) \cos \beta_j + (y_s - y_E) \sin \beta_j \right] \sin \alpha_i - (z_s - z_E) \cos \alpha_i} \right\}}$$

(5-83b)

5.3.6.1 (Continued)

The in-water azimuth is the same expression, while the in-water zenith angle is given by

$$\phi^{w}_{sij} = \sin^{-1}\left(\frac{1}{n}\sin\phi_{sij}\right), \tag{5-84}$$

for n = sea-water index of refraction.

If the receiver pointing angle is characterized by

G_{ELij} = zenith pointing angle

G_{AZij} = azimuth pointing angle (in the x_4, y_4, z_4 system), then the in-water angle between the signal and receiver axis is

$$\phi_{SRij} = \cos^{-1}\left\{\sin G_{ELij}\sin\phi^{w}_{sij}\ [\cos(G_{AZij}-\phi_{SAij})] + \cos G_{ELij}\cos\phi^{w}_{sij}\right\} \tag{5-85}$$

The solar and lunar off-receiver axis in-water pointing angles are derived in a like manner, using equation (5-6) for ϕ_{su} and equation (5-7) for ϕ_{mu}. Equations (5-1a through 5-1f) are the same form with

$R_s \rightarrow R_{su}$ (sun range),

and $R_s \rightarrow R_{mu}$ (moon range).

However, since $R_{su} \gg R_E$ and $R_{mu} \gg R_E$, the first (translation) transformation for the sun and moon becomes

$$x_2 = x_{su}\ (\text{or } x_{mu}), \tag{5-86a}$$

$$y_2 = y_{su}\ (\text{or } y_{mu}), \tag{5-86b}$$

$$z_2 = z_{su}\ (\text{or } z_{mu}), \tag{5-86c}$$

5.3.6.1 (Continued)

Moreover,

$$x_{su} = R_{su} \cos \alpha_{su} \cos \beta_{su}, \tag{5-87a}$$

$$y_{su} = R_{su} \cos \alpha_{su} \sin \beta_{su}, \tag{5-87b}$$

and $$z_{su} = R_{su} \sin \alpha_{su}. \tag{5-87c}$$

Then $x_2 \rightarrow x_3$ and $x_3 \rightarrow x_4$ proceed in the same manner as (5-81) and (5-82) with the results

$$\phi_{suA} = \tan^{-1} \left(\frac{y_4}{x_4} \right) ,$$

or

$$\boxed{\phi_{suAij} = \tan^{-1} \left\{ \frac{y_{su} \cos \beta_j - x_{su} \sin \beta_j}{(x_{su} \cos \beta_j + y_{su} \sin \beta_j) \sin \alpha_i - Z_{su} \cos \alpha_i} \right\}} \tag{5-88}$$

Also,

$$\boxed{\phi^{w}_{suij} = \sin^{-1} \left(\frac{1}{n} \sin \phi_{suij} \right)} \tag{5-89}$$

and

$$\boxed{\phi_{suRij} = \cos^{-1} \left\{ \sin G_{ELij} \sin \phi^{w}_{suij} [\cos (G_{AZij} - \phi_{suAij})] + \cos G_{ELij} \cos \phi^{w}_{suij} \cdot \right\}} \tag{5-90}$$

In like manner,

$$x_{mu} = R_{mu} \cos \alpha_{mu} \cos \beta_{mu}; \tag{5-91a}$$

$$y_{mu} = R_{mu} \cos \alpha_{mu} \sin \beta_{mu}; \tag{5-91b}$$

and $$z_{mu} = R_{mu} \sin \alpha_{mu}. \tag{5-91c}$$

5.3.6.1 (Continued)

and

$$\phi_{muAij} = \tan^{-1} \left\{ \frac{y_{mu} \cos \beta_j - x_{mu} \sin \beta_j}{(x_{mu} \cos \beta_j + y_{mu} \sin \beta_j) \sin \alpha_i - Z_{mu} \cos \alpha_i} \right\}$$

(5-92)

and

$$\phi^{w}_{muij} = \sin^{-1} \left(\frac{1}{n} \sin \phi_{muij} \right) \quad , \qquad (5\text{-}93)$$

so that

$$\delta_{muRij} = \cos^{-1} \left\{ \sin G_{ELij} \sin \phi^{w}_{muij} \left[\cos \left(G_{AZij} - \phi_{muAij} \right) \right] + \cos G_{ELij} \cos \phi^{w}_{muij} \cdot \right\}$$

(5-94)

Note that the parameters R_{su} and R_{mu} do not appear in the final result since they cancel out of (5-88) and (5-92) respectively.

For the diffuse sources, it is evident that

$$\delta_{BRij} = \delta_{ZRij} = G_{ELij} \qquad (5\text{-}95)$$

5.3.6.2 Laser Transmitter(s)

The transmitter is described by a much simpler model. We define

θ_T = full angle e^{-2} irradiance beam divergence;

E_p = energy per pulse at the laser transmitter;

PRF = pulse repetition frequency of the laser transmitter.

Then

$$\boxed{P_{AV} = (E_p)\ (PRF),} \tag{5-96a}$$

for P_{AV} = average power of the laser transmitter.

Since there may be more than one laser on a given satellite, we define

m = number of lasers (or terminals) per satellite, so that

mP_{AV} = total optical power capability of the satellite,

and $$\boxed{E_{PTOT} = mE_p.} \tag{5-96b}$$

If we then define

F_L = efficiency of the laser ("wall plug"), then

$$P_L{}' F_L = mP_{AV};\ \boxed{P_L{}' = \frac{mP_{AV}}{F_L}} \tag{5-96c}$$

for $P_L{}'$ = total prime power required on the satellite to sustain the lasers aboard.

In general, additional prime power will be required for other subsystems on the satellite, so we define

5.3.6.2 (Continued)

$P_{HO}^{\cdot}$ = prime power on the satellite required for all non-laser functions, and

$$\boxed{P_{TOT}^{\cdot} = P_L^{\cdot} + P_{HO}^{\cdot},} \tag{5-97}$$

for $P_{TOT}^{\cdot}$ = total prime power capability required on the satellite.

5.3.7 Availability/System Effectiveness and Adaptive Scanning

The final requirement to be covered is the availability or system effectiveness. This is a calculated value, depending on the system and propagation path inputs, and is compared to the requirement at the end of the entire calculation.

Availability of the communications downlink depends on both time and area, i.e., a part of the required area will be unavailable if the SNR is too low to communicate to it, or, if the system takes all the alloted time (T_A) communicating to the rest of the area.

This approach to availability suggests that if more than one active laser exists on each satellite, and if its characteristics could be modified to aid on other resolution elements, that availability might be thereby increased.

There are numerous possible variations of adaptive scanning, and we shall treat only three extremes here:

1. The totally non-adaptive system, which uses a single transmit beam divergence and energy per pulse over the entire area of responsibility;
2. A system which does not compensate for the environmental condition; but does compensate for zenith angle effects by varying its transmit beam width;
3. A system which compensates for all conditions.

5.3.7.1 Non-Adaptive Scanning

If the satellite has no information about the area it must communicate to, it will be assumed to meet the temporal aspects of availability first, and let the successful communications to a given spot be moot.

The first determinant of any scan pattern is the minimum angular spot size. We have previously developed the criterion for its selection:

> The long and short term angular jitter of the spacecraft, as expressed in (5-78) and (5-79).

We will investigate this constraint, and determine the minimum value of θ_T possible, and denote it as θ_{T1}.

5.3.7.1 (Continued)

Now, θ_{T1} will apply over the entire coverage area (for this totally non-adaptive scan). Then, within a given resolution element, all spots will have the useful area given by

$$\boxed{A_{RCTijMIN} = R_{ij}^2 \, \theta^2_{T1} \, (\cos \phi_{sij}) \, \varepsilon \, (1-\varepsilon^2)^{1/2},} \tag{5-98}$$

which is (5-74) with $D_{sp} = R_{ij}\theta_{T1}$ and $q = 1$.

The number of spots within the resolution element is given by

$$\boxed{N_{SREijMAX} = \frac{A_{RE}}{A_{RCTij}}} \tag{5-99}$$

and the total number of spots within the coverage area is given by

$$\boxed{N_{TOTSPMAX} = \sum_{ij} N_{SREijMAX}.} \tag{5-100}$$

Then, using (5-71b), the time it takes to cover the entire area with a single terminal is given by

$$\boxed{T_{TOTMAX} = (N_{TOTSPMAX}) \, (M_D) + (N_{TOTSPMAX}-1) \, t_{s\ell}.} \tag{5-101}$$

If $T_{TOTMAX} > T_A$, the only recourse left to the totally non-adaptive scan is to either increase θ_{T1} or to add more terminals which simultaneously use the old θ_{T1}.

Combining (5-98), (5-99), (5-100) and (5-101) we see that

$$T_{TOT} \propto \frac{1}{(\theta_{T1})^2}$$

5.3.7.1 (Continued)

and from the SPDPM,

$$\left.\frac{S}{N}\right)_{ij} \propto \frac{E_p}{(\theta_{T1})^2}.$$

Therefore, increasing θ_{T1} will decrease T_{TOT} and $\left.\frac{S}{N}\right)_{ij}$ equally, unless E_p is proportionately increased. So, adding a second terminal of equal energy onto the same spot means θ_{T1} may be increased by $\sqrt{2}$ for the same $\left.\frac{S}{N}\right)_{ij}$, while T_{TOT} is reduced by a factor of 2. Alternatively, adding a second terminal which operates independently will also maintain $\left.\frac{S}{N}\right)_{ij}$ and, by partitioning the resolution elements so that each terminal is responsible for half the total area, will result in the T_{TOT} for a given terminal being reduced by a factor of 2 from its previous value.

Evidently, then, the effect of adding a second terminal is independent of its actual mode of operation. We therefore assume that the temporal availability requirement is satisfied by the increase of

$\theta_{T1} \rightarrow \theta_{T2}$ so that

$T_{TOT} = T_A$, in (5-101).

The calculation procedure is to calculate (5-98) → (5-101), and if

$T_{TOT} > T_A$, define

$$\boxed{\theta_{T2} = \theta_{T1}\left(\frac{T_{TOTMAX}}{T_A}\right)^{1/2}} \quad (5\text{-}102)$$

Using θ_{T2} we now develop

$$\boxed{FOM_{ij} = \left.\frac{S}{N}\right)_{ij} \Big/ \left.\frac{S}{N}\right)_{REQ}} \quad (5\text{-}103)$$

5.3.7.1 (Continued)

for $\boxed{\left.\frac{S}{N}\right)_{REQ} = (MARG) \times \left.\frac{S}{N}\right).}$ (5-104a)

and $\left.\frac{S}{N}\right)$ in (5-104) is derived from the quality of service requirements for a given demodulation approach in Section 5.3.4.

MARG = system margin used to compensate for unmodelled noise sources, and

$\boxed{\left.\frac{S}{N}\right)_{ij} = \frac{\bar{P}_{Rij}}{NEP_{TOTij}},}$ for the ij resolution element from the SPDPM. (5-104b)

The availability is then simply given by the ratio of the areas for which $FOM_{ij} \geq 1$ to the total area responsibility, or,

$$\boxed{A_{VL} = \frac{\sum_{ij} A_{REij} \quad \text{(all ij such that } FOM_{ij} \geq 1)}{\sum_{ij} A_{REij}}} \qquad (5\text{-}105)$$

For diagnostic purposes, it is also useful to print out the minimum value of the FOM_{ij}, T_{TOT} if $T_{TOT} < T_A$, θ_{T1} and θ_{T2}.

5.3.7.2 One Partially Adaptive-Scanning Approach

We now consider a system which knows all the zenith angle aspects of its coverage area, but none of the environmental conditions. We assume that

(1) It controls the transmit beam divergence to compensate for the known zenith angle effects:

(2) Therefore it always uses circular spots;

(3) It compensates for zenith angle effects as if thick clouds were present, not clear weather, to assure maximum availability if thick clouds are indeed present.

5.3.7.2 (Continued)

The first determinant again is the minimum angular spot size, as discussed in Section 5.3.7.1. Use is also made of the FOM_{ij} defined in (5-103).

Given θ_{T1}, the minimum angular dimension, FOM_{ij} is evaluated for all the resolution elements for a nominal value of $\tau_{OPT} = 50$ throughout the coverage area. The smallest value of FOM_{ij} will normally occur at the largest zenith angle, and we denote it by FOM_{ss}. The transmit beam widths of each and every other FOM_{ij} are increased until

$$FOM_{ij} = FOM_{ss}.$$

In general the smallest values of τ_s will correspond to the largest increase in the transmit beam divergence. Since $FOM_{ij} \propto \frac{1}{(\theta_{Tij})^2}$, the increase in each transmit beam divergence is given by

$$\boxed{\theta_{Tij} = \theta_{T1}\left(\frac{FOM_{ij}\,(\theta_T = \theta_{T1})}{FOM_{ss}}\right)^{1/2}.} \tag{5-106}$$

Now θ_{Tij} will apply within a given resolution element, and will result in a useful coverage area

$$\boxed{A_{SCij} = c^2\, R^2_{ij}\, \theta^2_{Tij},} \tag{5-107}$$

where we have used $D_{sp} = R_{ij}\,\theta_{Tij}$. The number of spots within this resolution element is given by

$$\boxed{N_{SREij} = \frac{A_{RE}}{A_{SCij}},} \tag{5-108}$$

and the total number of spots within the coverage area is

$$\boxed{N_{TOTsp} = \sum_{ij} N_{SREij}\ .} \tag{5-109}$$

5.3.7.2 (Continued)

The time it takes to cover the entire area with a single terminal is

$$\boxed{T_{TOT} = (N_{TOTsp})\ (M_D) + (N_{TOTsp}-1)\ t_{s\ell}.} \qquad (5\text{-}110)$$

If $T_{TOT} > T_A$, we may again consider either increasing θ_{T1} or adding a second terminal. As for the totally non-adaptive scan, the net effect of adding a second terminal is independent of whether it is used to illuminate the same spot as the first terminal (allowing θ_{T1} to increase by $\sqrt{2}$), or separately illuminates spots of diameter θ_T.

We therefore assume that the temporal availability is satisfied by an increase of $\theta_{T1} \to \theta_{T2}$ so that $T_{TOT} = T_A$ in 5-110. The calculational procedure is to calculate (5-107) → (5-110) and if $T_{TOT} > T_A$, define

$$\boxed{\theta_{T2} = \theta_{T1} \left(\frac{T_{TOT}}{T_A} \right)^{1/2} .} \qquad (5\text{-}111)$$

since inspection of (5-107) → (5-110) shows that

$$T_{TOT} \propto \frac{1}{(\theta_{T1})^2}.$$

Given θ_{T2}, then, new values of θ_{Tij} are derived from

$$\boxed{\theta_{T2ij} = (\theta_{Tij}) \left(\frac{\theta_{T2}}{\theta_{T1}} \right).} \qquad (5\text{-}112)$$

In order to calculate the actual downlink availability, the FOM_{ij} are calculated for θ_{T2ij} and the actual environmental conditions present in each resolution element. The availability is then simply given by the ratio of the areas for which $FOM_{ij} \geq 1$ to the total area responsibility, or

5.3.7.2 (Continued)

$$A_{VL} = \frac{\underset{\text{(all } ij \text{ for which } FOM_{ij} \geq 1)}{\sum_{ij}} A_{REij}}{\sum_{ij} A_{REij}} . \tag{5-112}$$

For diagnostic purposes it is also useful to print out the value of T_{TOT} if $T_{TOT} < T_A$, θ_{T1}, θ_{T2} and the maximum value of θ_{T2ij}.

5.3.7.3 Availability for Fully Adaptive Scanning

In general, the resolution elements will present wildly varying values of $\left.\frac{S}{N}\right)_{ij}$ because of the differing environmental and angular properties present. It therefore makes sense to design a system which utilizes the excess signal in one area to compensate for a signal deficit in another area, if all conditions are known in advance to the satellite.

This adaptation of the scan parameters might be performed by

(1) Reducing the slot width, t_s, in clear weather areas. This would reduce the message duration, and allow more time for communicating to covered areas. However, it requires a source that could operate efficiently in widely differing modes, and a receiver with a foreknowledge of the slot width being used. For these reasons we discard this possibility.

(2) Increasing the spot diameter to the limit imposed by the $\left.\frac{S}{N}\right)_{REQ} = \left.\frac{S}{N}\right)_{ij}$. Thus the A_{RE} would be covered in less time, allowing extra time to cover the "bad" areas;

(3) Using multiple terminals to illuminate the same spot, so that the $\left.\frac{S}{N}\right)_{ij}$ is increased.

(4) Reducing the spot diameter in "bad" areas, to increase the $\left.\frac{S}{N}\right)_{ij}$. This is inadvisable since the minimum spot diameter is constrained by

(A) Long and short term satellite jitter;

(B) Submarine motion (equation 5-67)

(C) Enlargement in passing through the cloud.

5.3.7.3 (Continued)

Therefore we cannot arbitrarily reduce the D_{sp} to aid in bad weather communications†.

(5) Reducing submarine depth (smaller $|D|$). This should only be considered after all other expedients fail, since it does relieve a significant requirement.

In analyzing the adaptive scan, then, we assume

(1) The $\left.\frac{S}{N}\right)_{ij}$ will always be adjusted to be equal to $\left.\frac{S}{N}\right)_{REQ}$ by enlarging the spot diameter, and by adding additional terminals onto the same spot, as required.

(2) Only circular spots are considered, since the optical complexity is like that required for spot variation among resolutions elements.

We then begin, as before, by defining a minimum beam divergence θ_{T1}, based on the satellite jitter or submarine motion constraints. Given this θ_{T1}, a FOM_{ij} is derived for each resolution element, via

$$FOM_{ij} = FOM_{ij}\ (\theta_T = \theta_{T1}). \tag{5-114}$$

We again note that for $FOM_{ij}\ (\theta_T = \theta_{T1}) \geq 1$ for a single terminal, then if m terminals of equal energy per pulse are available on the satellite, the system performance cannot tell whether they are combined onto a single spot (enlarging θ_T) or separately used to illuminate spots of θ_{T1} size. For resolution elements with $FOM_{ij}\ (\theta_T = \theta_{T1}) < 1$ for a single terminal input of E_p, the optimum approach* is to use all available terminals to increase FOM_{ij} until it is > 1, and then increase the θ_{Tij} until $FOM_{ij} = 1$.

---

†However, it might be possible to use in-cloud spreading to reduce the required spot overlap.

*Or else, during some portion of T_A the total prime power capability of the satellite would be under-utilized while some areas were coverable but uncovered.

5.3.7.3 (Continued)

This implies that the very fact that there are m terminals is irrelevant to the availability analysis for this optimum adaptive scanning. Instead, FOM_{ij} should be evaluated as if all the available energy per pulse were present in a single beam.

When this is done, and FOM_{ij} evaluated in (5-114), for $FOM_{ij} < 1$ the resolution elements will not be covered. Hence the fundamentally unavailable area is

$$\boxed{A_{UNAV} = \frac{\sum\limits_{\substack{ij \\ (\text{for all } FOM_{ij}(\theta_T=\theta_{T1}) < 1)}} A_{REij}}{\sum\limits_{ij} A_{REij}}\ .} \tag{5-115}$$

On the other hand, for $FOM_{ij} > 1$, excess energy is being delivered, and the source being suboptimally utilized. We correct this by deriving

$$\boxed{\theta_{Tij} = \theta_{T1}\left[\frac{FOM_{ij}\ (\theta_T = \theta_{T1})}{1}\right]^{1/2}} \tag{5-116}$$

((since this means $FOM_{ij}\ (\theta_T = \theta_{Tij}) = 1$)), for all $FOM_{ij}\ (\theta_T = \theta_{T1}) \geq 1$.

We again use the effective coverage area of

$$\boxed{A_{scij} = \varepsilon^2\, R^2_{ij}\, \theta^2_{Tij}} \tag{5-117}$$

so that the number of spots per resolution element is

$$\boxed{N_{SREij} = \frac{A_{RE}}{A_{scij}}\ ,} \tag{5-118}$$

5.3.7.3 (Continued)

and the total number of spots is

$$N_{TOTSP} = \sum_{\substack{ij \\ \text{(for all } ij \text{ such that} \\ FOM_{ij}(\theta_T = \theta_{T1}) \geq 1)}} N_{SREij} \qquad (5\text{-}119)$$

Then the total time required to cover the entire coverable area is

$$T_{TOT} = N_{TOTSP} M_D + (N_{TOTSP} - 1)\, t_{si}. \qquad (5\text{-}120)$$

However, now if it happens that $T_{TOT} > T_A$, there is no recourse short of adding additional energy capability to the satellite, since there is no excess energy arriving at any submarine receiver. Indeed $T_{TOT} > T_A$ means that part of the area able to be covered from the SNR point of view is temporally unavailable.

To determine the availability, then, the time to scan each resolution element must be calculated. Moreover, since availability is a measure of area coverage, it makes sense to cover the resolution elements with the largest values of $FOM_{ij}\ (\theta_T = \theta_{T1})$ first, since they are using the largest spot diameter, θ_{Tij}.

We define the time to cover a given resolution element by

$$T_{ij} = N_{SREij}\,(M_D + t_{si}). \qquad (5\text{-}121)$$

and calculate

$$\sum_{ij} T_{ij} = T_{PART} \quad \left(\text{for } FOM_{ij}\ (\theta_T = \theta_{T1}) \geq 1, \text{ in order of largest to smallest}\right) \qquad (5\text{-}122)$$

until

$$T_{PART} > T_A. \qquad (5\text{-}122a)$$

5.3.7.3 (Continued)

The resolution element for which T_{PART} changes from $<T_A$ to $>T_A$ is denoted by the subscript o, t, and the fraction of its area covered is given by the fraction

$$\frac{T_A - T_{PART}\ (y_j = o,t-1).}{T_{o,t}}$$

Then the availability is given by

$$\boxed{A_{VL} = \frac{\sum\limits_{ij}^{ij = o,t-1} A_{REij}}{\sum\limits_{ij} A_{REij}} + \left|\frac{T_A - T_{PART}\ (ij = o,t-1)}{T_{o,t}}\right| .} \qquad (5\text{-}123)$$

It is also useful to print out A_{UNVL} (from 5-115), T_{TOT} (if $T_{TOT} > T_A$), θ_{T1} and the maximum value of θ_{Tij}, and the minimum and maximum values of N_{SREij}.

Note if $T_{TOT} \leq T_A$,

$$\boxed{A_{VL} = 1 - A_{UNAV}.} \qquad (5\text{-}124)$$

5.4 COMPUTER PROGRAM FOR THE DCM

5.4.1 Introduction

The downlink communication program is arranged as shown in Figure 5-11. There are eleven subroutines used in the program. These include the eight shown in the Figure; a general sorting subroutine (SORT); the single pulse model which has been incorporated into a subroutine (DSPDPM) called by FADAPT, PADAPT, and NADAPT; and a look-up table and interpolation subroutine (DSTRD2) called by DSPDPM.

There are four data files read into the program. The file SPPM contains that input data which is only used by the single pulse subroutine. The file ENVDATA contains the data from the environmental data bases, as well as the input data on the solar and lunar positions. Files DATAB and DATAC contain the input data concerning the satellite, laser, and signal processing and scanning requirements.

DMAIN is the mainline program used to read in the input data from the data files and to call the other subroutines. Subroutine DNCOMM is used to calculate all zenith angles, azimuthal angles, and receiver axis offset angles needed for the DCM. The range calculations from the satellite to the environmental resolution elements are also handled in this subroutine. The next subroutine called, SGPROC, is the subroutine that handles all signal-to-noise, jamming, spoofing, and message length computations for the downlink model. Subroutine POWER is used to perform the necessary energy and power calculations for the satellite and laser.

After these subroutines have been called and the necessary computation completed, a branch follows to one of three cases: fully adaptive scanning (FADAPT), partially adaptive scanning (PADAPT), or a non-adaptive scan (NADAPT). In these subroutines, the single pulse model subroutine (DSPDPM) is called upon to make signal-to-noise calculations for each environmental resolution element in the coverage area of that particular satellite. From these results, and temporal availability considerations, these subroutines perform the beam divergence, number of spots, and availability calculations that correspond to that particular mode of scanning.

The final subroutine called, ARYRIT, does all the printing and labeling of the output data.

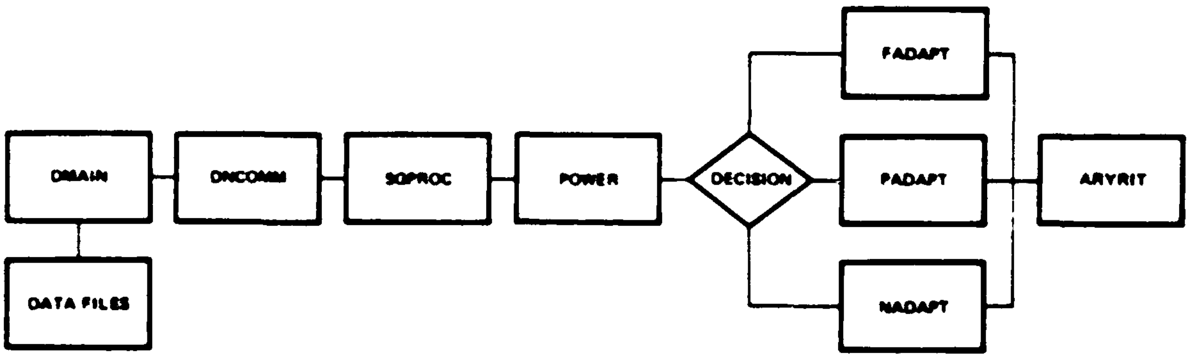

Figure 5-11. Layout of the DCM Program

5.4.2 Names of Variables

This section lists the Fortran terminology and definition of all variables used in the DCM which were not previously used and listed for the SPDPM.

A

ACARE =	Total area with signal-to-noise ratio greater than required signal-to-noise ratio
APAE = G_{AZ} =	Azimuthal pointing angle of receiver
ARE = A_{RE} =	Area of resolution elements
ASC = A_{SC} =	Area of square in spot
AUNAV = A_{UNAV} =	Fraction of the area that cannot be covered
AVL = A_{VL} =	Fraction of the area that can be covered
AZMUA = ϕ_{muA} =	Azimuthal lunar angles
AZSGA = ϕ_{SA} =	Azimuthal signal angle
AZSUA = ϕ_{suA} =	Azimuthal solar angles
AZMIN = $\theta_{SP_{min}}$ =	Minimum azimuthal angle from satellite

B

BITSP = ι =	Number of message bits per laser pulse
BMDIV = θ_T =	Beam divergence

C

COFOV = θ_R =	Half-angle of receiver field of view

D

DEADT = t_{ι} =	Dead time between frames
DEADTS = $t_{\iota S}$ =	Dead time between spots
DIVAD = θ_{TDR} =	Beam Divergence required due to satellite angular drift

5.4.2 (Continued)

DIVMIN = θ_{TMN} =		Minimum beam divergence required due to satellite restrictions.
DIVPJ = θ_{ts} =		Minimum beam divergence required due to satellige pointing jitter
DIVSAT =		Minimum beam divergence required due to satellite restrictions

E

EFF = F_L =	"Wall plug" efficiency of the laser
ETOT = E_{TOT} =	Total energy transmitted from all lasers per pulse

F

FOM = FOM =	Figure of merit, ratio of S/N in resolution element to S/N required for quality of service requirement

G

GAINSP = g =	"Gain" of spoof pulses relative to regular pulses

LATS, LATSR = λ_s; LATSU, LATSUR = λ_{su}; LATMU, LATMUR = λ_{mu} = Latitude of the satellite, sun, and moon in degrees and radians

LNGS, LNGSR = θ_s; LNGSU, LNGSUR = θ_{su}; LNGMU, LNGMUR = θ_{mu} = Longitude of the satellite, sun and moon in degrees and radians

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5.4.2 (Continued)

LATMR(I), LATMRR(I) = α_i; LNGMR(J), LNGMRR(J) = β_j	=	Mean latitude and longitude of the environmental resolution elements in degrees and radians

M

MARG = MARG = System margin used to compensate for unmodelled noise source

MAXR = $R_{ij_{max}}$ = Maximum range from satellite to any resolution element

MBITS = M_{LO} = Number of message bits

MESDUR = M_D = Total message duration

MLBITS = M_L = Total message length in bits

MAXZA = Maximum zenith angle from satellite to any resolution element

N

NCOL = Number of resolution elements along a line of constant latitude around the earth

NROW = Number of resolution elements in the northern hemisphere along a line of constant longitude

NJAM = N_J = Number of jammed pulses in threshold detection

NLASER = m = Number of lasers used on the satellite

NMISM = (N_m') = Number of missed messages per year

NPULSE = Number of pulses used to communicate to the coverage area

NRE = N_{TOTRE} = Number of resolution elements in the coverage area

NSPOOF = N_{SP} = Number of spoofing events per year

NSPOT(I,J) = $N_{SRE_{ij}}$ = Number of spots needed to cover the i, j resolution element

NTSPOT = N_{TOTSP} = Number of spots needed to cover the entire coverage area

5.4.2 (Continued)

NUMEF = w = Number of extra frames needed in message to reduce duplication probability to acceptable level

NJTOP2 = Number of jammed pulses using TOP processing

O

OVLAP = $\_$ = Spot overlap factor

OVHBTS = $M_{V\ell O}$ = Number of overhead bits

P

PROP = Number of resolution elements in northern hemisphere

PAVG = P_{AV} = Average power output from laser

PI = π = 3.1416

PLRE = Fraction of last resolution element that can be covered in the fully adaptive scan

PMISSM = P_M = Probability of missing a transmitted message

PNOLAS = P'_{HO} = Prime power (satellite) required for non-laser functions

PRF = PRF = Pulse repetition frequency of the laser

PTOT = P'_{TOT} = Prime power on satellite required

R

RE = R_E = Radius of the earth

RMU = R_{mu} = Distance from earth to the moon

RSU = R_{su} = Distance from earth to the sun

RITOP1 = An option to print (1.) or withold printing (0.) of the output data from DNCOMM

RITOP2 = An option to print (1.) or withold printing (0.) of the output data from DSPDPM

5.4.2 (Continued)

RNTYPE =	A decision variable. If it equals 1 a non-adaptive scan is employed, 2 is a partially adaptive scan, 3 is a fully adaptive scan
S	
SATSD = Dsp_{min} =	Minimum spot diameter due to scanning restrictions
SDMIN =	Minimum spot diameter
SFOM =	The sorted array of FOM values
SN = S/N =	The signal to noise ratio
SNREQ = $(S/N)_{REQ}$ =	Signal to noise ratio required by quality of service requirement
STIMRE =	The sorted array of TIMRE values
SUMI =	$\sum_i K_i D_i$
SPOPT =	A decision variable used to tell whether threshold detection or time-of-peak detection is to be used
T	
THW =	Thickness of first water layer
TIMAVL = T_A =	Time available to deliver message to coverage area
TIMEON = T_{on} =	Amount of time that laser is turned on
TIMRE(I,J) = T_{ij} =	Time necessary to cover a given resolution element
TSLOT = t_s =	Slot width
TTOTAL = T_{tot} =	Total time required to cover area of responsibility
TPART = T_{PART} =	The ΣT_{ij} in order of largest to smallest FOM_{ij} until it is greater than T_A
TSGNR = TNR =	Threshold signal to noise ratio

5.4.2 (Continued)

W

WARMUP = t_w = Time necessary for the laser to warmup

X

*XE = X_E = X coordinate of the submarine

*XS = X_S = X coordinate of the satellite

*XMU = X_{MU} = X coordinate of the moon

*XSU = X_{SU} = X coordinate of the sun

*In the earth centered system

Y

*YE = Y_E = Y coordinate of the submarine

*YS = Y_S = Y coordinate of the satellite

*YMU = Y_{MU} = Y coordinate of the moon

*YSU = Y_{SU} = Y coordinate of the sun

*In the earth centered system

Z

*ZE = Z_E = Z coordinate of the submarine

*ZS = Z_S = Z coordinate of the satellite

*ZSU = Z_{SU} = Z coordinate of the sun

*ZMU = Z_{MU} = Z coordinate of the moon

ZPAR = G_{EL} = Zenith pointing angle of the receiver

*In the earth centered system

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5.4.3 DMC Listing

This section lists the complete DCM program. The order of the subroutines listed is

DMAIN
DNCOMM
SGPROC
POWER
FADAPT
PADAPT
NAVAPT
ARYRIT
DSPDPM
SORT
DSTRD2

5.4.3 (Continued)

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```
      IMPLICIT REAL (A-Z)
      INTEGER I,J,NROW,NCOL,PROD,CA,CTHPIC,CTHGC
      DIMENSION THNPIC(1000),THGC(1000),NCHI(1000),V(1000),ZPAR(1000),
     1APAR(1000),ZASCA(1000),ZASA(1000),ZAMA(1000),ZASCW(1000),
     2ZASW(1000),ZAMW(1000),ADLTA(1000),ADLTAS(1000),ADLTAM(1000),
     3ADLTAP(1000),ADLTAZ(1000),R(1000),
     4LATHR(1000),LNGHR(1000),LATPHR(1000),LNGPHR(1000),AZSCA(1000),
     5AB(1000),VE(1000),ZE(1000),AZSWA(1000),AZMWA(1000),ZASCWB(1000),
     6ZASWB(1000),ZAMWB(1000),PHPCAB(1000),AEPIOT(1000),SN(1000),
     7AMOEV(1000),ASC(1000),ASPU(1000),PUM(1000),TIME(1000),
     8SIGMA(1000),STIME(1000),RI(1000),MN(1000),BR(6),BTHPIC(11),
     9BTHGC(11),BNCW(11),CA(1000),CTHPIC(1000),CTHGC(1000),CNCW(1000)
C
      NAMELIST /AINPUT/NROW,NCOL,ARE,BSU,LATSU,LNGSU,BMU,LATMU,LNGMU,
     1RE,THNPIA,D,NDEX,BITOPI,CTHPIC,CTHGC,CNCW,V,RNTYPE,CB,IMO/BINPUT/
     2TIMAW,NPP,VSUBR,NBITS,NPISH,GAINSP,D,SPCPT/CINPUT/WEADIS,PDF,
     3BEASPR,ET,EFF,PNDLAS,PS,LATS,LNGS,DEADT,TSLOT,BITSP,OVLAP,CIVPJ,
     4CIVAC,WARMUP,MAPG/LATINW/LATPP,LNGPP
C
      DATA ZPAR/100000.0/,APAR/100000.0/
C     INITIALIZATION OF ZPAR TO ALLOW FOR VARIABLE DIMENSION IN SUBRTN
C
      DATA BR/0.,.031,.047,.111/
      DATA BTHPIC/-1.,0.,3.5,5.0,6.9,26.7,21.,42.6,89.,309.,303.9/
      DATA BTHGC/200.,20500.,50100C.,300C.,6000./
      DATA BNCW/200.,400C.,1001.,400C.,2500.,20500.,2500.,201000./
C
C     VALUES TO DECODE CA,CTHPIC,CTHGC, CNCW(ATTENUATION OF WATER,
C     OPTICAL AND GEOMETRIC THICKNESS OF THE CLOUDS, DISTANCE, CLOUD
C     BASE TO WATER SURFACE
C
   10 READ(8,AINPUT)
   20 READ(9,BINPUT)
   30 READ(10,CINPUT)
   40 READ(11,LATINW)
C
      PROD=NROW*NCOL
C     PROD IS USED FOR SCALING IN FABAPI
C     PROD IS USED FOR FINDING ROLIV VALUES FOR B, THNPIC, AND THGC
C
C
C     LOOP TO DECODE B,THNPIC, AND THGC FOLLOWS
      DO 45 J=1,PROD
      B(J)=BR(CA(J)+1)
      THNPIC(J)=BTHPIC(CTHPIC(J)+1)
      THGC(J)=BTHGC(CTHGC(J)+1)
      NCW(J)=BNCW(CNCW(J)+1)
   45 CONTINUE
C
C
C     CHECK TO SEE IF SCAN TYPE HAS BEEN PROPERLY DECLARED.
C     1.=NON-ADAPTIVE, 2.=PARTIALLY ADAPTIVE, 3.=FULLY ADAPTIVE.
C
      IF(RNTYPE.NE.1.0.AND.RNTYPE.NE.2.0.AND.RNTYPE.NE.3.0)GO TO 9000
C
C     THE FOLLOWING DETERMINES THE TYPE OF SCAN BEING USED
C
```

5.4.3 (Continued)

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```
      IF(RNTYPE.EQ.1.0)WRITE(6,50)
   50 FORMAT('1'/////1X,40('*'),'THIS RUN IS A NON-ADAPTIVE SCAN',
     $40('*'))
C
      IF(RNTYPE.EQ.2.0)WRITE(6,60)
   60 FORMAT('1'/////1X,35('*'),'THIS RUN IS A PARTIALLY ADAPTIVE SCAN',
     $35('*'))
C
      IF(RNTYPE.EQ.3.0)WRITE(6,70)
   70 FORMAT('1'/////1X,37('*'),'THIS RUN IS A FULLY ADAPTIVE SCAN',
     $37('*'))
C
C     THE FOLLOWING OUTPUTS INPUT PARAMETERS
C
      WRITE(6,100)DSU,DMU,LATSU,LATMU,LNGSU,LNGMU,ARE,THOPTA,RE,C,NDEX,
     $RITOPT,NCOL,NROW,RNTYPE
C
      CALL ARYRIT(1,NROW,NCOL,THOPTC)
      CALL ARYRIT(2,NROW,NCOL,THGC)
      CALL ARYRIT(3,NROW,NCOL,PCW)
      CALL ARYRIT(4,NROW,NCOL,VI)
      CALL ARYRIT(10,NROW,NCOL,RI)
      CALL ARYRIT(11,NROW,NCOL,THW)
C
      WRITE(6,200)TIMAVL,ARE,VSUBM,NBITS,NMISM,GAINSP,D,SPOPT
C
      WRITE(6,300)DEADTS,PRF,NLASER,ET,EPF,PNOLAS,RS,LATS,LNGS,DEACT,
     $ISLOT,DIISP,OVLAP,DIVPJ,DIVAD,WARMUP,MANG
C
C
  100 FORMAT('1'/////54X,10('*'),'INPUT',10('*')////1X,'DSU   =',E12.5,
     $5X,'DISTANCE FROM SUN TO RECEIVER',14X,'DMU   =',E12.5,5X,'DISTANC
     $E FROM MOON TO RECEIVER'/1X,'LATSU =',E12.5,5X,'LATITUDE-SUN REL T
     $O EARTH CENTER',11X,'LATMU =',E12.5,5X,'LATITUDE-MOON REL TO EARTH
     $CENTER'/1X,'LNGSU =',E12.5,5X,'LONGITUDE-SUN REL TO EARTH CENTER',
     $10X,'LNGMU =',E12.5,5X,'LONGITUDE-MOON REL TO EARTH CENTER'/1X,
     $'ARE   =',E12.5,5X,'AREA OF RESOLUTION ELEMENTS',16X,'THOPTA=',
     $E12.5,5X,'CLEAR ATMOS OPTICAL THICKNESS'/1X,'RE    =',E12.5,5X,
     $'MEAN EARTH RADIUS',26X,'C     =',E12.5,5X,'PARAMETER DESCRIBING T
     $YPE LASER SPOT USED'/1X,'NDEX  =',E12.5,5X,'WATER INDEX OF REFRACT
     $ION',18X,'RITOPT=',E12.5,5X,'WRITE OPTION FOR DHCOMM SUBROUTINE'/
     $1X,'NCOL  =',I12,5X,'COLUMN DIMENSION FOR ARRAYS IN RUN',9X,
     $'NROW  =',I12,5X,'ROW DIMENSION FOR ARRAYS IN RUN'/1X,'RNTYPE=',
     $E12.5,5X,'TYPE OF SCAN BEING RUN')
C
  200 FORMAT('1'/////54X,10('*'),'DINPUT',10('*')////1X,'TIMAVL=',E12.5,
     $5X,'COVERAGE TIME',30X,'ARE   =',E12.5,5X,'NO. OF RESOL ELEMENTS I
     $N COVERAGE AREA'/1X,'VSUBM =',E12.5,5X,'MAXIMUM VELOCITY OF SUBMAR
     $INE',14X,'NBITS =',E12.5,5X,'MESSAGE LENGTH IN BITS'/1X,'NMISM =',
     $E12.5,5X,'NUMBER OF MISSED MESSAGES PER YEAR',9X,'GAINSP=',
     $E12.5,5X,'GAIN OF SPCOP PULSES REL TO REG PULSES'/1X,'D     =',
     $E12.5,5X,'SUBMARINE DEPTH',28X,'SPOPT =',E12.5,5X,
     $'SIGNAL PROCESSING OPTION')
C
  300 FORMAT('1'/////54X,10('*'),'CINPUT',10('*')////1X,'DEADTS=',E12.5,
     $5X,'DEAD TIME BETWEEN SPOTS',20X,'PRF   =',E12.5,5X,'PULSE REPETI
     $TION FACTOR'/1X,'NLASER=',E12.5,5X,'NUMBER OF LASERS USED',22X,'ET
```

5.4.3 (Continued)

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ELWOJ.ORBIN.FCRT
05/02/79

```
$      =',E12.5,5X,'ENERGY TRANSMITTED'/1X,'EFF      =',E12.5,5X,'EFFICIE
$NCY OF LASER WALL PLUG',1X8,'PKLAS= ',E12.5,  5X,'PRIME PWR ON SAT
$ REQ FOR NON-LASER FUNCS'/1X,'PS      =',E12.5,5X,'ALTITUDE OF SATEL
$LITE',22X,'LATS  =',E12.5,5X,'LATITUDE OF SATELLITE'/1X,'LNGS  =',
$E12.5,5X,'LONGITUDE OF SATELLITE',21X,'DEAD  =',E12.5,5X,'DEAD TIME
$S BETWEEN FRAMES'/1X,'ISLOT =',E12.5,5X,'SLOT WIDTH',31X,'BITSP =
$,E12.5,5X,'BITS PER PULSE'/1X,'OVLAP =',E12.5,5X,'SPOT OVERLAP FAC
$TOR',24X,'DIVPJ =',E12.5,5X,'ANGULAR DIVERGENCE REQ-POINTING JITTE
$R'/1X,'DIVAD =',E12.5,5X,'ANGULAR DIVERGENCE REQ-ANGULAR DRIFT',/1
$,'WARMUP=',E12.5,5X,'LASER WARMUP TIME'/1X,'MARG  =',E12.5,5X,'SI
$GNAL-TO-NOISE RATIO FACTOR')
C
C
C     THE FOLLOWING SECTION CALLS APPROPRIATE SUBROUTINES, ACCORDING
C     TO INPUT DATA AND SCAN TYPE USED.  EACH SUBROUTINE IS DEFINED
C     AFTER THE SUBROUTINE STATEMENT.
C
C
      CALL ONEFRAME(NROW,NCOL,BITOPT,INOPTC,PSC,RMU,LATMR,LNGMR,
     $LATS,LATSU,LATMU,LNGS,LNGSU,LNGMU,JPAR,APAR,RE,RS,NUER,MARB,
     $ZASGA,ZASA,ZAMA,ZASGU,ZASU,ZAMU,DELTA,DELTAS,DELTAM,DELTAB,DELTAZ,
     $P,LATMPR,LNGMPR,AZSGA,RE,RP,ZE,
     $AZSUB,AZMUB,ZASGWD,ZASWD,ZAMWD)
C
C
      CALL SGPROC(SPOPT,NNISH,TIMAVE,BITSP,GAINSP,NBITS,ISLOT,
     $VSMDR,OVLAP,DEADT,DEADTS,DIVAD,DIVPJ,RADD,RRE,ARE,SNR,DIVRIN,
     $NISRWD)
C
C
      CALL POWER(NNISH,TIMAVE,ET,PRF,PLASER,EFF,PKOLAS)
C
C
C     THE FOLLOWING CALLS THE PROPER SUBROUTINE FOR THE SCAN USED
C
      IF(SNTYPE-2.)4000,5000,6000
C
C     NON-ADAPTIVE SCAN
 4000 CALL NADAPT(NROW,NCOL,PRCD,INOPTA,INGC,INOPTC,NCU,V,R,TMU,Q,ZASGA,
     1DELTA,ZASA,ZAMA,DELTAS,DELTAM,DELTAB,DELTAZ,ISLOT,MARG,SNR,ARE,
     2DIVRIN,OVLAP,R,MESCUR,DEADTS,WARMUP,TIMAVE,RRE,PRF,
     3PPPEAK,NEPTOT,SN,BPDIV,ASC,NSPCT,PCR)
      GO TO 9999
C
C     PARTIALLY ADAPTIVE SCAN
 5000 CALL PADAPT(NROW,NCOL,INOPTA,INGC,INOPTC,NCU,V,R,TMU,Q,ZASGA,
     1DELTA,ZASA,ZAMA,DELTAS,DELTAM,DELTAB,DELTAZ,ISLOT,MARG,SNR,ARE,
     2DIVRIN,OVLAP,R,MESCUR,DEADTS,WARMUP,TIMAVE,RRE,PRF,
     3PPPEAK,NEPTOT,SN,BPDIV,ASC,NSPCT,PCR)
      GO TO 9999
C
C     FULLY ADAPTIVE SCAN
 6000 CALL FADAPT(NROW,NCOL,PRCD,INOPTA,INGC,INOPTC,NCU,V,R,TMU,Q,ZASGA,
     1DELTA,ZASA,ZAMA,DELTAS,DELTAM,DELTAB,DELTAZ,ISLOT,MARG,SNR,ARE,
     2DIVRIN,OVLAP,R,MESCUR,DEADTS,WARMUP,TIMAVE,RRE,PRF,
     3PPPEAK,NEPTOT,SN,BPDIV,ASC,NSPCT,SOUP,STIPPE,
     4TTIM,TIMPT)
```

5.4.3 (Continued)

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                                                                        PAGE 0004
                                                            ISUBJ.DRAIN.FORT
                                                            05/02/79  09:25:10
      GO TO 9999                                                        00001530
C                                                                       00001540
C                                                                       00001550
C                                                                       00001560
 9000 WRITE(6,9001)                                                     00001570
 9001 FORMAT(1X,25('*'),'ERROR.  SCAN TYPE HAS NOT BEEN PROPERLY DECLARE00001580
     $D.  CHECK VARIABLE RNTYPE.',25('*'))                              00001590
C                                                                       00001600
C                                                                       00001610
 9999 STOP                                                              00001620
      END                                                               00001630
```

5.4.3 (Continued)

TSO83.DNCUMM.FORT
05/02/79 09:33:09

```
      SUBROUTINE DNCOMM(NROW,NCOL,ALTOPT,THOPTC,ASU,AMU,/LATMR/,/LNGMR/,
     &LATS,LATSU,LATMU,LNGS,LNGSU,LNGMU,ZPAR,APAR,RE,RS,NDEX,MAXR,
     &ZASGA,ZASA,ZAMA,ZASGU,ZASU,ZAMU,ADLTA,ADLTAS,ADLTAM,ADLTAB,ADLTAZ,
     &R,/LATMRR/,/LNGMRR/,/AZSGA/,/RE/,/VE/,/ZE/,
     &/AZSUA/,/AZMUA/,/ZASGUD/,/ZASUD/,/ZAMUD/)
      IMPLICIT REAL (A-Z)
      INTEGER I,J,NROW,NCOL
      DIMENSION LATMR(NROW),LATMRR(NROW),LNGMR(NCOL),LNGMRR(NCOL),
     &ZASA(NROW,NCOL),ZAMA(NROW,NCOL),R(NROW,NCOL),
     &ZASGA(NROW,NCOL),ZPAR(NROW,NCOL),APAR(NROW,NCOL),ADLTA(NROW,NCOL),
     &ADLTAS(NROW,NCOL),ADLTAM(NROW,NCOL),ADLTAB(NROW,NCOL),
     &ADLTAZ(NROW,NCOL),AZSGA(NROW,NCOL),RE(NROW,NCOL),VE(NROW,NCOL),
     &ZE(NROW,NCOL),ZASGU(NROW,NCOL),AZSUA(NROW,NCOL),ZASU(NROW,NCOL),
     &AZMUA(NROW,NCOL),ZAMU(NROW,NCOL),ZASGUD(NROW,NCOL),
     &ZASUD(NROW,NCOL),ZAMUD(NROW,NCOL),THOPTC(NROW,NCOL)
      PI=2.*ARCOS(0.0)
C
      DO 10 I=1,NROW
   10 LATMRR(I)=LATMR(I)*PI/180.
      DO 20 J=1,NCOL
   20 LNGMRR(J)=LNGMR(J)*PI/180.
C
C     CONVERSION SECTION--INPUT PARAMETERS,DEGREES TO RADIANS.
C
   30 LATSR=LATS*PI/180.
      LATSUR=LATSU*PI/180.
      LATMUR=LATMU*PI/180.
      LNGSR=LNGS*PI/180.
      LNGSUR=LNGSU*PI/180.
      LNGMUR=LNGMU*PI/180.
C
      MAXR=0.0
C     MAXR WILL BE MAXIMUM VALUE IN R ARRAY
C
C     CALCULATION OF ZENITH ANGLES
C
      DO 100 J=1,NCOL
      DO 90 I=1,NROW
      ZASGA(I,J)=91.*PI/180.
      ZASA(I,J)=0.
      ZAMA(I,J)=0.
      R(I,J)=0.
      IF(THOPTC(I,J).LT.0.)GO TO 90
   40 ZASA(I,J)=ARCOS(.5*(COS(LATMRR(I)+LATSUR)*(COS(LNGMRR(J)-LNGSUR)
     &-1.)+COS(LATMRR(I)-LATSUR)*(COS(LNGMRR(J)-LNGSUR)+1.)))
C
C     SOLAR IN-ATM ZENITH ANGLE
C
   50 ZAMA(I,J)=ARCOS(.5*(COS(LATMRR(I)+LATMUR)*(COS(LNGMRR(J)-LNGMUR)
     &-1.)+COS(LATMRR(I)-LATMUR)*(COS(LNGMRR(J)-LNGMUR)+1.)))
C
C     LUNAR IN-AIR ZENITH ANGLE
C
   60 R(I,J)=((RE+RS)**2+RE**2-RE*(RE+RS)*(COS(LATMRR(I)+LATSR)*(COS
     &(LNGMRR(J)-LNGSR)-1.)+COS(LATMRR(I)-LATSR)*(COS(LNGMRR(J)-LNGSR)
     &+1.)))**.5
C
```

5.4.3 (Continued)


```
C     RANGE FROM SATELLITE TO RESOLUTION ELEMENTS
C
   70 IF(R(I,J).GT.MAXR) MAXR=R(I,J)
C     CHECK TO FIND MAXIMUM VALUE IN R ARRAY
C
   80 ZASGA(I,J)=ARCOS((1./R(I,J))*((RE+RS)/2.*((COS(LNGMAR(J)
     $-LNGSA)-1.)*COS(LATMAR(I))*LATSA)
     $*COS(LATMAR(I)-LATSA)*(COS(LNGMAR(J)-LNGSA)+1.))-R(I))
C
C     SIGNAL IN-AIR ZENITH ANGLE
C
  211 XE(I,J)=RE*COS(LATMAR(I))*COS(LNGMAR(J))
  212 YE(I,J)=RE*COS(LATMAR(I))*SIN(LNGMAR(J))
  213 ZE(I,J)=RE*SIN(LATMAR(I))
C     SUBMARINE COORDINATES (RADIANS)
   90 CONTINUE
  100 CONTINUE
  221 XS=(RE+RS)*COS(LATSA)*COS(LNGSA)
  222 YS=(RE+RS)*COS(LATSA)*SIN(LNGSA)
  223 ZS=(RE+RS)*SIN(LATSA)
C     SATELLITE COORDINATES (RADIANS)
C
  231 XSU=(RE+RSU)*COS(LATSUN)*COS(LNGSUN)
  232 YSU=(RE+RSU)*COS(LATSUN)*SIN(LNGSUN)
  233 ZSU=(RE+RSU)*SIN(LATSUN)
C     SOLAR COORDINATES (RADIANS)
C
  241 XMU=(RE+RMU)*COS(LATMUN)*COS(LNGMUN)
  242 YMU=(RE+RMU)*COS(LATMUN)*SIN(LNGMUN)
  243 ZMU=(RE+RMU)*SIN(LATMUN)
C     LUNAR COORDINATES
C
C     CALCULATIONS FOR THOPTC.GE.10.0(120-190)
C
  120 DO 740 J=1,NCOL
      DO 710 I=1,NROW
      IF(THOPTC(I,J).LT.0.)GO TO 125
      IF(THOPJC(I,J).LT.10.)GO TO 300
  125 ZASGW(I,J)=0.0
      ZASW(I,J)=0.0
      ZAMW(I,J)=0.0
      ZASGWD(I,J)=ZASGW(I,J)
      ZASWD(I,J)=ZASW(I,J)
      ZAMWD(I,J)=ZAMW(I,J)
C     CONVERSION TO DEGREES FOR OUTPUT (VALUE IS 0.)
      ZPAR(I,J)=ZASGWD(I,J)
C     EVALUATION OF ZENITH PTING ANGLE (IN DEGREES)
      AZMUA(I,J)=0.0
      AZSGA(I,J)=0.0
      AZSUA(I,J)=0.0
C     DUMMIES TO BE PASSED TO SPOPM
      ZASGA(I,J)=ZASGA(I,J)*180./PI
      ZASA(I,J)=ZASA(I,J)*180./PI
      ZAMA(I,J)=ZAMA(I,J)*180./PI
      ADLTA(I,J)=ZPAR(I,J)
      ADLTAS(I,J)=ZPAR(I,J)
      ADLTAM(I,J)=ZPAR(I,J)
```

5.4.3 (Continued)

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ESDBJ.TMCUAM.FORT
05/22/79 09:33:09

```
      ADLTAB(I,J)=ZPAR(I,J)
      ADLTAZ(I,J)=ZPAR(I,J)
  190 GO TO 730
C
C     CALCULATIONS FOR THIPTY.LT.10.0 (300-720)
C
C
C
  300 AZSGA(I,J)=ATAN2((YS-YE(I,J))*COS(NGMAR(J))-(XS-XE(I,J))*SIN(N
     1MAR(J)),((XS-XE(I,J))*COS(NGMAR(J))+(YS-YE(I,J))*SIN(NGMAR(J)))*
     2)*SIN(LATMAR(I))-(ZS-ZE(I,J))*COS(LATMAR(I))))
C     AZIMUTHAL SIGNAL ANGLES (RADIANS)
  305 IF (AZSGA(I,J).LT.0.0)AZSGA(I,J)=AZSGA(I,J)+(2.0*PI)
C     CORRECTION FOR RANGE OF AZSGA (0<AZSGA<=2.*PI)
      APAR(I,J)=AZSGA(I,J)*180./PI
C     CALCULATION OF APAR IN DEGREES
C
  310 ZASGW(I,J)=ARSIN(SIN(ZASGA(I,J))/NDEX)
C     SIGNAL IN-WATER ZENITH ANGLES
C
      ZASGWD(I,J)=ZASGW(I,J)*180./PI
      ZASGA(I,J)=ZASGA(I,J)*180./PI
C     CONVERSION TO DEGREES
      ZPAR(I,J)=ZASGWD(I,J)
C     EVALUATION OF ZENITH PTING ANGLE (IN DEGREES)
C
  320 ADLTA(I,J)=(ARCOS(SIN(ZPAR(I,J)*PI/180.)*SIN(ZASGW(I,J))*COS((APAR
     1(I,J)*PI/180.)-AZSGA(I,J))+COS(ZPAR(I,J)*PI/180.)*COS(ZASGW
     2(I,J))))*180./PI
C     OFFSET ANGLE BTWN RECVR OPT AXIS AND AXIS OF INCOMING LT (DEGREES)
C
      AZSGA(I,J)=AZSGA(I,J)*180./PI
C     CONVERSION TO DEGREES
C
  400 AZSUA(I,J)=ATAN2((YSU*COS(NGMAR(J))-XSU*SIN(NGMAR(J))),((XSU*COS
     1(NGMAR(J))+YSU*SIN(NGMAR(J)))*SIN(LATMAR(I))-ZSU*COS(LATMAR(I)))
     2)
C     AZIMUTHAL SOLAR ANGLES (RADIANS)
  405 IF (AZSUA(I,J).LT.0.0)AZSUA(I,J)=AZSUA(I,J)+(2.0*PI)
C     CORRECTION FOR RANGE OF AZSUA (0<AZSUA<=2.*PI)
C
  410 ZASW(I,J)=ARSIN(SIN(ZASA(I,J))/NDEX)
C     SOLAR IN-WATER ZENITH ANGLE
      ZASWD(I,J)=ZASW(I,J)*180./PI
      ZASA(I,J)=ZASA(I,J)*180./PI
C     CONVERSION TO DEGREES
C
  420 ADLTAS(I,J)=(ARCOS(SIN(ZPAR(I,J)*PI/180.)*SIN(ZASW(I,J))*COS((APAR
     1(I,J)*PI/180.-AZSUA(I,J))+COS(ZPAR(I,J)*PI/180.)*COS(ZASW(I,J))))
     2*180./PI
C     OFFSET ANGLE BTWN RECVR OPT AXIS AND AXIS OF INCOMING LT (DEGREES)
      AZSUA(I,J)=AZSUA(I,J)*180./PI
C     CONVERSION TO DEGREES
C
C
  900 AZMJA(I,J)=ATAN2((YMJ*COS(NGMAR(J))-XMJ*SIN(NGMAR(J))),((XMJ*COS
     1(NGMAR(J))+YMJ*SIN(NGMAR(J)))*SIN(LATMAR(I))-ZMJ*COS(LATMAR(I)))
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5.4.3 (Continued)

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ESIAJ,ONCOMA,FORT
05/22/77 09:33:09

```
     *)
C      AZIMUTHAL LUNAR ANGLES
  505 IF (AZMUA(I,J).LT.0.0)AZMUA(I,J)=AZMUA(I,J)+2.*PI)
C     CORRECTION FOR RANGE OF AZMUA (0<AZMUA< 2.*PI)
C
  510 ZAMU(I,J)=ARSIN(SIN(ZAMA(I,J))/NOFA)
C     LUNAR IN WATER ZENITH ANGLE
      ZAMUO(I,J)=ZAMU(I,J)*180./PI
      ZAMA(I,J)=ZAMA(I,J)*180./PI
C     CONVERSION TO DEGREES
C
  520 ADLTAM(I,J)=(ARCOS(SIN(ZPA(I,J)*PI/180.)*SIN(ZAMU(I,J))*COS(APAR
     &(I,J)*PI/180.-AZMUA(I,J))+COS(ZPA(I,J)*PI/180.)*COS(ZAMU(I,J))))
     &*180./PI
C     OFFSET ANGLE BTWN RECVR OPT AXIS AND AXIS OF INCOMING LT (DEGREES)
C
      AZMUA(I,J)=AZMUA(I,J)*180./PI
C     CONVERSION TO DEGREES
C
  620 ADLTAB(I,J)=ZPA(I,J)
C     OFFSET ANGLE BTWN RECVR OPT AXIS AND AXIS OF INCOMING LT (DEGREES)
C
  720 ADLTAZ(I,J)=ZPA(I,J)
C     OFFSET ANGLE BTWN RECVR OPT AXIS AND AXIS OF INCOMING LT (DEGREES)
C
  730 CONTINUE
  740 CONTINUE
 1000 IF (ATTOP1.EQ.0.0) GO TO 3000
C
C     THE FOLLOWING PRINTS INTERMEDIATE INPUTS AND CALCULATIONS
C
      WRITE(6,1005)
 1005 FORMAT('1'/////60X,10('*'),'OUTPUT FROM ONECOMA',10('*'))
      WRITE(6,1010)LATMA
 1010 FORMAT(///64X,'LATMA'/60X,'LATITUDES OF PTS WITHIN COVERAGE AREA'/
     &(1X,10E12.5))
      WRITE(6,1020)LNGMA
 1020 FORMAT(///64X,'LNGMA'/60X,'LONGITUDES OF PTS WITHIN COVERAGE AREA'
     &/(1X,10E12.5))
 1040 CALL ARYRIT(7,NROW,NCOL,ZASA)
 1050 CALL ARYRIT(8,NROW,NCOL,ZAMA)
 1060 CALL ARYRIT(9,NROW,NCOL,R)
      WRITE(6,1065)MAXR
 1065 FORMAT('1'//////1X,'THE MAXIMUM VALUE IN ARRAY R IS',E12.5)
 1070 CALL ARYRIT(10,NROW,NCOL,ZASGA)
 1211 CALL ARYRIT(11,NROW,NCOL,XE)
 1212 CALL ARYRIT(12,NROW,NCOL,YE)
 1213 CALL ARYRIT(13,NROW,NCOL,ZE)
      WRITE(6,1221)XS,YS,ZS
 1221 FORMAT('1'/////56X,'SATELLITE COORDINATES'//1X,'XS=',E12.5/1X,
     &'YS=',E12.5/1X,'ZS=',E12.5)
      WRITE(6,1231)XSU,YSU,ZSU
 1231 FORMAT('1'/////56X,'SOLAR COORDINATES'//1X,'XSU=',E12.5/1X,
     &'YSU=',E12.5/1X,'ZSU=',E12.5)
      WRITE(6,1241)XMU,YMU,ZMU
 1241 FORMAT('1'/////56X,'LUNAR COORDINATES'//1X,'XMU=',E12.5/1X,
     &'YMU=',E12.5/1X,'ZMU=',E12.5)
```

GTE SYLVANIA

5.4.3 (Continued)

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                                                                                    PAGE 0005
                                                                [illegible]
                                                                05/02/79    09.11.09
1300  CALL  ARVRIT(116,NROW,NCOL,[illegible])                   00001077
1250  CALL  ARVRIT(110,NROW,NCOL,[illegible])                   00001078
1310  CALL  ARVRIT(115,NROW,NCOL,[illegible])                   00001079
1350  CALL  ARVRIT(15,NROW,NCOL,[illegible])                    00001080
1450  CALL  ARVRIT(116,NROW,NCOL,[illegible])                   00001081
1410  CALL  ARVRIT(117,NROW,NCOL,[illegible])                   00001082
1500  CALL  ARVRIT(118,NROW,NCOL,[illegible])                   00001083
1510  CALL  ARVRIT(119,NROW,NCOL,[illegible])                   00001084
2000  CALL  ARVRIT(120,NROW,NCOL,[illegible])                   00001085
2420  CALL  ARVRIT(121,NROW,NCOL,[illegible])                   00001086
2520  CALL  ARVRIT(122,NROW,NCOL,[illegible])                   00001087
2620  CALL  ARVRIT(123,NROW,NCOL,[illegible])                   00001088
2720  CALL  ARVRIT(124,NROW,NCOL,[illegible])                   00001089
C                                                               00001090
3000  RETURN                                                    00001091
      END                                                       00001092
```

5.4.3 (Continued)

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TSOBJ.SGPROC.FORT
05/02/79 [illegible]

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      SUBROUTINE SGPROC(SPOPT,NMISM,TIPAVE,BITSP,GAINSP,NBITS,TSLOT,
     1VSMOD,OVLAP,DEADT,DEADTS,DIVAD,DIVPJ,RAJD,ARE,ARE,SAR,DIVMIN,
     2MESDUR)
      IMPLICIT REAL(A-Z)
C     PROGRAM WILL BRANCH TO HANDLE THRESHOLD OR TIME OF PEAK DETECTION
      TSGAM=0.0
      IF(SPOPT.GT.0.0)GO TO 130
C
C     THIS SECTION USES THRESHOLD DETECTION PROCESSING
C
   20 TSGAM=(-2.0ALOG(3.46.5NMISM*TIPAVE/((2.**BITSP-1.)*3.1557E07)))**
     10.5
C     CALCULATE THRESHOLD TO NOISE RATIO
   30 SNR=((-2.0ALOG(2.0)...[illegible]...3.1557E07)))**0.5+(-2.0ALOG(2.
     10).46.5NMISM*TIPAVE/((2.**BITSP-1.)*3.1557E07)))**0.5
C     PER YEAR
C  32 NUMEF=0.0
C     CALCULATE NUMBER OF EXTRA FRAMES
   35 NLBITS=NBITS
C     CALCULATE THE TOTAL NUMBER OF BITS PER MESSAGE
   40 RSPOOF=(2.**BITSP*(GAINSP*NLBITS/BITSP)*(TSLOT/TIPAVE)*((1.-(GAINSP
     1*NLBITS/BITSP)*(TSLOT/TIPAVE)))**(NLBITS/BITSP)*3.1557E07/(NLBIT
     2S*TSLOT*2.**BITSP/BITSP)*DEADT*(NLBITS/BITSP-1.))
C     CALCULATE THE NUMBER OF SPOOFING PULSES PER YEAR
   50 RJAM=((1.-(1.-(GAINSP*NLBITS/BITSP)*(TSLOT/TIPAVE)))**((2.**BITSP-1
     1.)*(NLBITS/BITSP)+2.**BITSP+1.))*(3.1557E07/TIPAVE)
C     CALCULATE THE NUMBER OF JAMMING EVENTS PER YEAR
      GO TO 200
C
C     THIS SECTION USES TIME OF PEAK SIGNAL PROCESSING
C
  130 SNR=SNTOP(NMISM,TIPAVE,BITSP)
C     CALCULATE SIGNAL TO NOISE RATIO THAT ALLOWS NMISM MISSED MESSAGES
C     PER YEAR
  132 NUMEF=AINT((20.91-1.44*ALOG(TSLOT*BITSP))/BITSP)
C     CALCULATE NUMBER OF EXTRA FRAMES
  135 NLBITS=NBITS+NUMEF*BITSP
C     CALCULATE THE TOTAL NUMBER OF BITS PER PULSE
  140 RSPOOF=3.1557E07*(GAINSP*TSLOT*NLBITS/(BITSP*TIPAVE))**NUMEF*((1./
     1(NLBITS*TSLOT*2.**BITSP/BITSP+(NLBITS/BITSP-1.)*DEADT))
C     CALCULATE THE NUMBER OF SPOOFING EVENTS PER YEAR
  150 RJAM=3.1557E07*NUMEF*(1./TIPAVE)*(2.**BITSP-1.)**2*(GAINSP*TSLOT*
     1NLBITS/(BITSP*TIPAVE))**2
C     CALCULATE THE NUMBER OF JAMMING PULSES PER YEAR
C
C
  200 MESDUR=NLBITS*TSLOT*2.**BITSP/BITSP+(NLBITS/BITSP-1.)*DEADT
C     CALCULATE TOTAL MESSAGE DURATION
      DIVSAT=10.*(DIVPJ**2+DIVAD**2)**0.5
C     CALCULATE THE MINIMUM BEAM DIVERGENCE DUE TO SATELLITE RESTRICTIONS
      SATSD=RAJD*(DIVSAT*3.1416/180.)
C     CALCULATE THE MINIMUM SPOT SIZE DUE TO SATELLITE RESTRICTIONS
  250 DIVMIN=DIVSAT
  260 IF(SWDSD.GT.SATSD)GO TO 270
      SDMIN=SATSD
      GO TO 280
  270 SDMIN=SWDSD
```

GTE SYLVANIA

5.4.3 (Continued)

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(SGRJ.SGPROC.FORT)
05/02/79 09:32:16

```
C     FINDS THE MINIMUM BEAM DIVERGENCE AND SPOT DIAMETER OBTAINABLE
  280 ASC=(DIVLAP*SDMIN)**2
C     CALCULATE AREA OF SQUARE IN SPOT
      NSPOT=ARE/ASC
C     CALCULATE THE NUMBER OF SPOTS IN ONE RESOLUTION ELEMENT
      NTSPOT=NRE*NSPOT
C     CALCULATE THE TOTAL NUMBER OF SPOTS IN THE COVERAGE AREA
      TTOTAL=NTSPOT*MESDUR+(NTSPOT-1.)*DEADTS
C     CALCULATE TOTAL TIME REQUIRED TO COVER AREA OF RESPONSIBILITY
      WRITE(6,290)
  290 FORMAT('1'/////40X,10('*'),'OUTPUT FROM SGPROC',10('*'))
      WRITE(6,300)TSNR
  300 FORMAT(/1X,E12.5,5X,'TSNR',11X,'THRESHOLD TO NOISE RATIO')
      WRITE(6,310)SNR
  310 FORMAT(/1X,E12.5,5X,'SNR',13X,'SIGNAL TO NOISE RATIO')
      WRITE(6,320)NSPOOF
  320 FORMAT(/1X,E12.5,5X,'NSPOOF',10X,'NUMBER OF SPOOFING EVENTS PER YE
     1AR')
      WRITE(6,330)NJAM
  330 FORMAT(/1X,E12.5,5X,'NJAM',12X,'NUMBER OF JAMMING EVENTS PER YEAR'
     1)
      WRITE(6,340)NUMEF
  340 FORMAT(/1X,E12.5,5X,'NUMEF',11X,'NUMBER OF EXTRA FRAMES')
      WRITE(6,350)MBITS
  350 FORMAT(/1X,E12.5,5X,'MBITS',10X,'TOTAL MESSAGE LENGTH BITS')
      WRITE(6,360)MESDUR
  360 FORMAT(/1X,E12.5,5X,'MESDUR',10X,'TOTAL MESSAGE DURATION')
      WRITE(6,390)SATSD
  390 FORMAT(/1X,E12.5,5X,'SATSD',11X,'MINIMUM SPOT DIAMETER DUE TO SATE
     1LLITE RESTRICTIONS')
      WRITE(6,400)DIVSAT
  400 FORMAT(/1X,E12.5,5X,'DIVSAT',10X,'MINIMUM BEAM DIVERGENCE DUE TO S
     1ATELLITE RESTRICTIONS')
      WRITE(6,410)SDMIN
  410 FORMAT(/1X,E12.5,5X,'SDMIN',11X,'MINIMUM SPOT DIAMETER DUE TO SYST
     1EM RESTRICTIONS')
      WRITE(6,420)DIVMIN
  420 FORMAT(/1X,E12.5,5X,'DIVMIN',10X,'MINIMUM BEAM DIVERGENCE DUE TO S
     1YSTEM RESTRICTIONS')
      WRITE(6,430)ASC
  430 FORMAT(/1X,E12.5,5X,'ASC',13X,'AREA OF SQUARE IN SPOT')
      WRITE(6,440)NSPOT
  440 FORMAT(/1X,E12.5,5X,'NSPOT',11X,'NUMBER OF SPOTS IN ONE RESOLUTION
     1 ELEMENT')
      WRITE(6,450)NTSPOT
  450 FORMAT(/1X,E12.5,5X,'NTSPOT',10X,'NUMBER OF SPOTS IN TOTAL COVERAG
     1E AREA')
      WRITE(6,460)TTOTAL
  460 FORMAT(/1X,E12.5,5X,'TTOTAL',10X,'TOTAL TIME REQUIRED TO COVER ARE
     1A OF RESPONSIBILITY')
      RETURN
      END
      FUNCTION SATOP(AMESP,TIMAVE,BITSP)
      IMPLICIT REAL(A-Z)
      INTEGER I
      E=AMESP*TIMAVE*(2.0)*1.6E+00.5/(12.0*BITSP-1.)*3.155760E07)
      G=ALOG(E)
```

5.4.3 (Continued)

```
                                                                        PAGE 0003
                                                            ISOBJ.SCPROC.FORT
                                                            05/02/79  09132116
      SAD=5.                                                00001185
C     MAKE INITIAL GUESS AT VALUES OF ROOTS                 00001190
   50 DO 1 I=1,120                                          00001200
      F=G*ALOG(SAD)+SAD**2/2.                               00001210
      DF=1./SAD+SAD                                         00001220
      A=SAD                                                 00001230
      SAD=A-F/DF                                            00001240
      IF(ABS(A-SAD).LT.1.E-6)GO TO 2                        00001250
    1 CONTINUE                                              00001260
C     ITERATION TO FIND ROOTS VIA NEWTON-RALPHSON METHOD    00001270
    2 SAIGP=SAD                                             00001280
      RETURN                                                00001290
      END                                                   00001300
```

5.4.3 (Continued)

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T5OBJ.POWER.FORT
05/02/79

```
      SUBROUTINE POWER(NMISP,TIMAVL,ET,PRF,HLASER,EFF,PWLAS)
      IMPLICIT REAL (A-Z)
   10 PMISSN=NMISSP/(TIMAVL/3.15576E7)
   20 PAVG=ET*PRF
   30 ETOT=HLASER*ET
   40 PRIMEP=HLASER*PAVG/EFF
   50 PTOT=PRIMEP+PWLAS
C
C
C      ************OUTPUT************
C
C
      WRITE(6,100)
  100 FORMAT('1'//////50X,10('*'),'OUTPUT FROM POWER SUBROUTINE',10('*'))
      WRITE(6,110)PMISSN
  110 FORMAT(/1X,E12.5,5X,'PMISSN',10X,'PROB. OF MISSED MESSAGE')
      WRITE(6,120)PAVG
  120 FORMAT(/1X,E12.5,5X,'PAVG',12X,'AVERAGE PWR OUTPUT FROM LASER')
      WRITE(6,130)ETOT
  130 FORMAT(/1X,E12.5,5X,'ETOT',12X,'TOTAL ENERGY TRANSMITTED')
      WRITE(6,140)PRIMEP
  140 FORMAT(/1X,E12.5,5X,'PRIMEP',10X,'TOTAL PRIME POWER USED')
      WRITE(6,150)PTOT
  150 FORMAT(/1X,E12.5,5X,'PTOT',12X,'TOT PRIME PWR CAP ON SATELLITE')
      RETURN
      END
```

5.4.3 (Continued)

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TSOBJ.FADAPT.FORT
05/02/76 (144513)

```
      SUBROUTINE FADAPT(NROW,NCOL,PRED,INOPTA,INCC,INOPIC,NCW,V,E,TNW,C,
     1ZASGA,ADLTA,ZASA,ZAMA,ADLTAS,ADLTAP,ADLTAD,ADLTAZ,TSLOT,RANG,SNR,
     2ADE,DIVMIN,CULAP,B,NESCUB,BEADIS,BADPUP,IIRAVE,NRE,PRF,
     6/PPPEAK/,/NEPTOT/,/SN/,/BNDIV/,/ASC/,/ASPOT/,/SFUN/,/STIME/,
     7/FOR/,/TIME/)
C
      IMPLICIT REAL (A-Z)
C
C
      INTEGER I,J,KK,L,NRCW,NCCL,PROB,COUNT
C
      DIMENSION INCC(NROW,NCOL),INOPIC(NROW,NCOL),NCW(NROW,NCOL),
     2ZASGA(NROW,NCOL),ADLTA(NROW,NCOL),ZASA(NROW,NCOL),ZAMA(NROW,NCOL),
     3ADLTAS(NROW,NCOL),ADLTAM(NROW,NCOL),ADLTAD(NROW,NCOL),
     4ADLTAZ(NROW,NCOL),V(NROW,NCOL),PPPEAK(NROW,NCOL),
     5NEPTOT(NROW,NCOL),SN(NROW,NCOL),FNDIV(NROW,NCOL),
     6ASC(NROW,NCOL),E(NROW,NCOL),ASPOT(NROW,NCOL),SFUN(PROB),
     7STIME(PROB),FOR(NROW,NCOL),TIPP(NROW,NCOL),
     8E(NROW,NCOL),TNW(NROW,NCOL)
C
      PI=2.0*ARCOS(0.0)
      SNRTC=RANG*SNR
      TPART=0.0
      W=0.
      M=0.
      N=0.
      L=0
      AISPOT=0.0
      COUNT=0
C     INITIALIZE COUNTING VARIABLES TO 0.0
C
      ATDWF=DIVMIN
      IFIRST=1.0
      WRITE(6,1)
    1 FORMAT('1'/////40X,10('*'),'OUTPUT FROM DSPOPR',10('*'))
C
      DO 10 J=1,NCOL
      DO 10 I=1,NROW
      SN(I,J)=0.0
      IF(ZASGA(I,J).GE.90.0)GO TO5
      CALL DSPOPR(INOPTA,INCC(I,J),INOPIC(I,J),ATDWF,NCW(I,J),V(I,J),
     2E(I,J),TNW(I,J),0,ZASGA(I,J),ADLTA(I,J),ZASA(I,J),ZAMA(I,J),
     3ADLTAS(I,J),ADLTAM(I,J),ADLTAD(I,J),ADLTAZ(I,J),TSLOT,E(I,J),
     8IFIRST,PPPEAK(I,J),NEPTOT(I,J))
      COUNT=COUNT+1
      IF(COUNT.EQ.50)WRITE(6,1)
      IF(COUNT.EQ.50)COUNT=0
  990 WRITE (6,9990)ZASGA(I,J),PPPEAK(I,J),NEPTOT(I,J),I,J
 9990 FORMAT (1X,'ZASGA=',E12.5,10X,'PPPEAK=',E12.5,10X,'NEPTOT=',E12.5,
     815X,'COORDINATES',3X,'(',I3,',',I3,')'/)
      IFIRST=0.0
      SN(I,J)=PPPEAK(I,J)/NEPTOT(I,J)
C     CALCULATE SIGNAL TO NOISE RATIO FOR (I,J) ELEMENT
C
    5 FON(I,J)=SN(I,J)/SNRTC
C     CALCULATE RATIO OF SIGNAL TO NOISE RECEIVED TO SIGNAL TO NOISE RC
C
```

5.4.3 (Continued)


```
      IF (FOM(I,J).GT.1.0) GO TO 15                                 00000570
C                                                                   00000580
C     COUNT NUMBER OF ELEMENTS WITH FOM.LT.1.0                      00000590
C                                                                   00000600
   12 BMDIV(I,J)=0.0                                                00000610
   13 ASC(I,J)=0.0                                                  00000620
   14 NSPOT(I,J)=0.0                                                00000630
C     ZERO IN SPOT VARIABLES FOR ELEMENTS NOT COVERED               00000640
C                                                                   00000650
      GO TO 10                                                      00000660
C                                                                   00000670
   15 M=M+1.                                                        00000680
C     COUNT NUMBER OF ELEMENTS WITH FOM.GT.1.0                      00000690
C                                                                   00000700
  112 BMDIV(I,J)=DIVMIN*FOM(I,J)**.5                                00000710
C     CALCULATE BEAM DIVERGENCE REQD. TO OBTAIN THE REQD. S/N RATIO 00000720
C                                                                   00000730
  113 ASC(I,J)=(CVLAP*R(I,J)*BMDIV(I,J)*PI/180.)**2                 00000740
C     CALCULATE AREA OF SQUARE IN SPOT                              00000750
C                                                                   00000760
  114 NSPOT(I,J)=AINT(ARE/ASC(I,J))+1.0                             00000770
C     CALCULATE NUMBER OF SPOTS IN RESOLUTION ELEMENT               00000780
C                                                                   00000790
  116 NTSPOT=NTSPOT+NSPOT(I,J)                                      00000800
C     CALCULATE TOTAL NUMBER OF SPOTS IN COVERAGE AREA              00000810
C                                                                   00000820
   10 CONTINUE                                                      00000830
C                                                                   00000840
C                                                                   00000850
      ACARE=M*ARE                                                   00000860
C     CALCULATE TOTAL AREA WITH S/N.GT.THE REQD S/N RATIO           00000870
C                                                                   00000880
   17 TTOTAL=NTSPOT*NPSOLD+(NTSPOT-1.)*DEADT                        00000890
C     CALCULATE TIME NEEDED TO COVER ALL ELEMENTS WITH S/N.GT.S/N REQD 00000900
C                                                                   00000910
      IF(TTOTAL.GT.TIMAVL) GO TO 110                                00000920
C     BRANCH POINT TO DETERMINE WHETHER OR NOT ALL ELEMENTS WITH    00000930
C     SUFFICIENT S/N CAN BE COVERED IN SUFFICIENT TIME.  IF THEY CAN'T 00000940
C     ALL BE COVERED, A SPECIAL ROUTINE WHICH CALCULATES MAXIMUM    00000950
C     AVAILABLE COVERAGE IN THE ALLOTTED TIME WILL BE USED.         00000960
C                                                                   00000970
C                                                                   00000980
   18 TIMEON=WARMUP+TTOTAL                                          00000990
C     CALCULATE THE TOTAL TIME THE LASER IS TURNED ON               00001000
C                                                                   00001010
      AUNAV=(NAE-M)/NAE                                             00001020
      WRITE(6,500)AUNAV                                             00001030
  500 FORMAT('1','FRACTION OF AREA THAT CANNOT BE COVERED(AUNAV)=',F3.2)00001040
C     CALCULATE FRACTION OF AREA THAT CANNOT BE COVERED             00001050
C                                                                   00001060
   19 AVL=1.-AUNAV                                                  00001070
C     CALCULATE FRACTION OF AREA THAT CAN BE COVERED                00001080
C                                                                   00001090
C                                                                   00001110
C                                                                   00001120
C     **********TTOTAL.GT.TIMAVL ROUTINE**********                  00001130
C                                                                   00001140
```

5.4.3 (Continued)

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FSDB1.FADAPT.FORT
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```
C
  110 TIMECN=WARMUP+TIMAVL
C     CALCULATE TOTAL TIME LASER IS TURNED ON
C
      DO 20 J=1,NCOL
      DO 20 I=1,NROW
      TIMRE(I,J)=NSPOT(I,J)*(TIMESUM+LEADIS)
      K=K+1
      SFOM(K)=FOM(I,J)
   20 STIMRE(K)=TIMRE(I,J)
C     CALCULATE TIME REQUIRED TO SCAN EACH ELEMENT
C
      CALL SORT(SFOM,STIMRE,NRCO)
  999 WRITE (6,9999)(SFOM(I),STIMRE(I),I=1,NRCO)
 9999 FORMAT (6X,'SFOM',23X,'STIMRE',/(1X,E12.5,10X,E12.5))
C
      IF(TTOTAL.LT.TIMAVL)GO TO 23
      DO 30 KK=1,NRCO
      TPART=TPART+STIMRE(KK)
      IF (TPART.GT.TIMAVL) GO TO 21
   30 CONTINUE
C
   21 TPART=TPART-STIMRE(KK)
   22 PLRE=(TIMAVL-TPART)/STIMRE(KK)
C     CALCULATE FRACTION OF LAST RESOLUTION ELEMENT THAT CAN BE COVERED
C
  119 AVL=(FLOAT(KK)-1.)+PLRE)/NRE
C     CALCULATE FRACTION OF COVERAGE AREA THAT CAN BE COVERED IN
C     THE TIME AVAILABLE
C
   23 NPULSE=TIMEON*PRF
C     CALCULATE THE NUMBER OF PULSES REQUIRED DURING OPERATION
C
C
C
      WRITE(6,290)
  290 FORMAT('1'/////40X,10('*'),'OUTPUT FROM FADAPT',10('*'))
 1011 CALL ARYRIT(25,NROW,NCOL,FOM)
 1012 CALL ARYRIT(26,NROW,NCOL,RECIV)
 1013 CALL ARYRIT(27,NROW,NCOL,ASC)
 1014 CALL ARYRIT(28,NROW,NCOL,NSPOT)
C
      CALL ARYRIT(29,NROW,NCOL,TIMRE)
      WRITE(6,1021)TPART
 1021 FORMAT('1'/////,1X,E12.5,5X,'TPART',11X,'TIME NEEDED TO COVER ALL
     1ST RESOLUTION ELEMENT')
      WRITE(6,1022)STIMRE(KK)
 1022 FORMAT(/,1X,E12.5,5X,'STIMRE',11X,'TIME NEEDED TO COVER LAST RESOL
     1UTION ELEMENT')
C
 1245 WRITE(6,1016)NTSPOT
 1016 FORMAT('1'/////1X,F12.5,5X,'NTSPOT',10X,'TOTAL NUMBER OF SPOTS REQ
     1D')
      WRITE(6,1017)TTOTAL
 1017 FORMAT(/1X,F12.5,5X,'TTOTAL',10X,'TOTAL TIME NEEDED TO COVER ALL A
     1VAILABLE RESOLUTION ELEMENTS')
C
```

GTE SYLVANIA
ELECTRONIC SYSTEMS GROUP
EASTERN DIVISION

5.4.3 (Continued)

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                              ESORJ.FADAPT.FORT
                              05/02/75  (5:45:35)

      WRITE(6,1019)AVE                                                  00001710
 1019 FORMAT(/,1X,E12.5,5X,'AVE',11X,'FRACTION OF COVERAGE AREA THAT IS 00001720
     2AVAILABLE')                                                       00001730
      WRITE(6,1020)TIMEON                                               00001740
 1020 FORMAT(/,1X,E12.5,5X,'TIMEON',10X,'TOTAL TIME LASER IS TURNED ON')00001750
      WRITE(6,1023)NPULSE                                               00001770
 1023 FORMAT(/,1X,E12.5,5X,'NPULSE',10X,'NUMBER OF LASER PULSES FIRED') 00001780
      RETURN                                                            00001790
      END                                                               00001800
```

5.4.3 (Continued)

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TSO03.PADAPT.FORT
05/02/79 09:47:49

```
      SUBROUTINE PADAPT(NROW,NCOL,THOPTA,THGC,THOPTC,HCW,V,R,THW,Q,
     1ZASGA,ADLTA,ZASA,ZAMA,ADLTAS,ADLTAM,ADLTAB,ADLTAZ,TSLOT,MARG,SNR,
     2ARE,DIVMIN,OVLAP,A,NESCAN,DEADTS,WARMUP,TIMAVL,NRE,PRF,
     3/PPPEAK/,/NEPTOT/,/SN/,/BMDIV/,/ASC/,/NSPOT/,/FOM/)
C
      IMPLICIT REAL(A-Z)
      INTEGER KK,N,I,J,NROW,NCOL,COUNT
C
      DIMENSION THGC(NROW,NCOL),THOPTC(NROW,NCOL),HCW(NROW,NCOL),
     1ZASGA(NROW,NCOL),ADLTA(NROW,NCOL),ZASA(NROW,NCOL),ZAMA(NROW,NCOL),
     3ADLTAS(NROW,NCOL),ADLTAM(NROW,NCOL),ADLTAB(NROW,NCOL),
     4ADLTAZ(NROW,NCOL),V(NROW,NCOL),PPPEAK(NROW,NCOL),
     5NEPTOT(NROW,NCOL),SN(NROW,NCOL),BMDIV(NROW,NCOL),
     6ASC(NROW,NCOL),R(NROW,NCOL),NSPOT(NROW,NCOL),FOM(NROW,NCOL),
     7R(NROW,NCOL),THW(NROW,NCOL)
C
C
      N=0
      KK=0
      NTSPOT=0.0
      IFIRST=1.0
      COUNT=0
C     INITIALIZE COUNTING VARIABLES AND READ OP FOR FILE 7 IN DSPOPR
C
      WRITE(6,1)
    1 FORMAT('1'/////50X,10('*'),'OUTPUT FROM DSPOPR',10('*'))
C
      DO 100 J=1,NCOL
      DO 100 I=1,NROW
      ATBWP=DIVMIN
      SN(I,J)=0.
      IF(ZASGA(I,J).GT.90.)GO TO 100
      CALL DSPOPR(THOPTA,THGC(I,J),THOPTC(I,J),ATBWP,HCW(I,J),V(I,J),
     1R(I,J),THW(I,J),Q,ZASGA(I,J),ADLTA(I,J),ZASA(I,J),ZAMA(I,J),
     2ADLTAS(I,J),ADLTAM(I,J),ADLTAB(I,J),ADLTAZ(I,J),TSLOT,R(I,J),
     3IFIRST,PPPEAK(I,J),NEPTOT(I,J))
      COUNT=COUNT+1
      IF(COUNT.EQ.50)WRITE(6,1)
      IF(COUNT.EQ.50)COUNT=0
  777 WRITE (6,7777)ZASGA(I,J),PPPEAK(I,J),NEPTOT(I,J),I,J
 7777 FORMAT (1X,'ZASGA=',E12.5,10X,'PPPEAK=',E12.5,10X,'NEPTOT=',E12.5,
     115X,'COORDINATES',3X,'(',I3,',',I3,')'/)
      SNREQ=MARG*SNR
      IFIRST=0.0
   10 SN(I,J)=PPPEAK(I,J)/NEPTOT(I,J)
C     CALCULATE SIGNAL TO NOISE RATIO FOR MINIMUM BEAM DIVERGENCE
   11 FOM(I,J)=SN(I,J)/SNREQ
C     CALCULATE S/N TO S/N REQD. RATIO FOR MINIMUM BEAM DIVERGENCE
      KK=KK+1
      IF(KK.EQ.1)FOMSS=FOM(I,J)
      IF(FOM(I,J).LT.FOMSS)FOMSS=FOM(I,J)
  100 CONTINUE
      DO 16 J=1,NCOL
      DO 16 I=1,NROW
      BMDIV(I,J)=0.
      ASC(I,J)=0.
      NSPOT(I,J)=0.
```

5.4.3 (Continued)

TSOBJ.PADAPT.FORT
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```
      IF(THOPT(I,J).LT.0.)GO TO 16                                       00000580
      IF(ZASGA(I,J).GT.90.0)GO TO 16                                   * 00000585
   12 BMDIV(I,J)=DIVMIN*(FOM(I,J)/FOMSS)**.5                             00000590
C     ADJUST BEAM DIVERGENCE SO ALL RES. ELEMENTS HAVE FOM=FOMSS         00000600
   13 ASC(I,J)=(OVLAP*R(I,J)*BMDIV(I,J))**2                              00000610
C     CALCULATE AREA OF SQUARE IN SPOT FOR THIS BEAM DIVERGENCE          00000623
   14 NSPOT(I,J)=AINT(ARE/ASC(I,J)+1.)                                   00000633
C     CALCULATE NUMBER OF SPOTS IN RESOLUTION ELEMENT                    00000640
      NTSPOT=NTSPOT+NSPOT(I,J)                                           00000653
   16 CONTINUE                                                           00000660
C     CALCULATE NUMBER OF SPOTS IN COVERAGE AREA                         00000670
C                                                                        00000680
   17 TTOTAL=NTSPOT*RESDWL+(NTSPOT-1.)*DEADTS                             00000690
C     CALCULATE TOTAL TIME REQD. TO COVER ALL RES. ELEMENTS              00000700
C                                                                        00000710
C                                                                        00000720
      WRITE(6,250)                                                       00000730
  250 FORMAT('1'//////40X,10('*'),'OUTPUT FROM PADAPT',10('*'))          00000740
 1011 CALL ARYRIT(25,NROW,NCOL,FOM)                                      00000750
 1012 CALL ARYRIT(26,NROW,NCOL,BMDIV)                                    00000760
 1013 CALL ARYRIT(27,NROW,NCOL,ASC)                                      00000770
 1015 CALL ARYRIT(28,NROW,NCOL,NSPOT)                                    00000780
      WRITE(6,1016)NTSPOT                                                00000785
 1016 FORMAT(/1X,E12.5,5X,'NTSPOT',10X,'TOTAL NUMBER OF SPOTS REQD. FOR  00000793
     $ABOVE BEAM DIVERGENCE')                                            00000803
      WRITE(6,1017)TTOTAL                                                00000810
 1017 FORMAT(/1X,E12.5,5X,'TTOTAL',10X,'TOTAL TIME NEEDED TO COVER ALL $00000820
     $AVAILABLE RESOLUTION ELEMENTS')                                    00000830
C                                                                        00000840
C                                                                        00000850
      IF(TTOTAL.GE.TIMAVL)GO TO 110                                      00000860
   18 TIMEON=WARMUP+TTOTAL                                               00000870
C     CALCULATE TIME LASER IS TURNED ON                                  00000880
C                                                                        00000890
      COUNT=0                                                            00000900
      WRITE(6,1)                                                         00000905
      DO 300 J=1,NCOL                                                    00000910
      DO 300 I=1,NROW                                                    00000920
      IF(ZASGA(I,J).LT.90.0)GO TO 800                                    00000930
      FOM(I,J)=0.0                                                       00000940
      GO TO 300                                                          00000950
  800 ATBMF=BMDIV(I,J)                                                   00000960
      COUNT=COUNT+1                                                      00000970
      IF(COUNT.EQ.50)WRITE(6,1)                                          00000980
      IF(COUNT.EQ.50)COUNT=0                                             00000990
      CALL DSPOPN(THOPTA,THGC(I,J),THOPT(I,J),ATBMF,HCW(I,J),V(I,J),     00001000
     $R(I,J),TRW(I,J),0,ZASGA(I,J),ADLTAT(I,J),ZASAT(I,J),ZAMAT(I,J),    00001010
     $ADLTAS(I,J),ADLTAM(I,J),ADLTAB(I,J),ADLTAZ(I,J),TSLOT,R(I,J),      00001020
     $IFIRST,PAPEAK(I,J),NEPTOT(I,J))                                    00001030
  998 WRITE (6,999)ZASGA(I,J),PPPEAK(I,J),NEPTOT(I,J),I,J                00001031
C                                                                        00001032
  110 SN(I,J)=PAPEAK(I,J)/NEPTOT(I,J)                                    00001053
C     CALCULATE SIGNAL TO NOISE RATIO FOR BMDIV ADJUSTED SO FOM=FOMSS    00001068
  111 FOM(I,J)=SN(I,J)/SNREQ                                             00001070
C     CALCULATE RATIO OF S/N TO S/N REQUIRED                             00001080
      IF(FOM(I,J).GE.1)N=N+1                                             00001090
  300 CONTINUE                                                           00001100
```

5.4.3 (Continued)

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TSOBJ.PADAPT.FORT
05/02/79 09:47:49

```
      GO TO 19
C
  110 TIMEON=WARMUP+TIMAVL
C     CALCULATE TIME LASER IS ON
C
      COUNT=0
      DO 500 J=1,NCOL
      DO 500 I=1,NROW
      IF(ZASGA(I,J).LT.90.0)GO TO 900
      FOM(I,J)=0.0
      GO TO 500
C
  900 ATBWF=BWDIV(I,J)*(TOTAL/TIMAVL)**.5
C     ADJUST BEAM DIVERGENCE SO TOTAL AREA CAN BE SCANNED IN TIME AVAIL.
C
      CALL QSPQPB(IWRT(4,IWGS(I,J),IWGT(I,J),ATBWF,HSV(I,J),VI(I,J),
     $R(I,J),TM(I,J),0,ZASGA(I,J),ADLTA(I,J),ZASA(I,J),ZAMA(I,J),
     $ADLTAS(I,J),ADLTAM(I,J),AMTAB(I,J),ADLTAZ(I,J),TSLOT,R(I,J),
     $IFIRST,PPEAK(I,J),NEPTOT(I,J))
       COUNT=COUNT+1
       IF(COUNT.EQ.50)WRITE(6,1)
       IF(COUNT.EQ.50)COUNT=0
  999 WRITE (6,999)ZASGA(I,J),PPEAK(I,J),NEPTOT(I,J),I,J
C
  210 SN(I,J)=PPEAK(I,J)/NEPTOT(I,J)
C     CALCULATE SIGNAL TO NOISE RATIO
  211 FOM(I,J)=SN(I,J)/SNREQ
C     CALCULATE RATIO OF S/N TO S/N REQUIRED
      IF(FOM(I,J).GE.1.0)N=N+1
  500 CONTINUE
C
C
   19 AVL=N/NRF
C     CALCULATE FRACTION OF COVERAGE AREA THAT IS AVAILABLE
   23 NPULSE=PRF*TIMEON
C     CALCULATE THE NUMBER OF LASER PULSES REQUIRED
 2011 CALL ARYRIT(25,NROW,NCOL,FOM)
 2012 CALL ARYRIT(26,NROW,NCOL,NADIV)
 1265 WRITE(6,1019)AVL
 1019 FORMAT('1'/////,1X,E12.5,5X,'AVL',13X,'FRACTION OF COVERAGE AREA T
     2HAT IS AVAILABLE')
      WRITE(6,1018)TIMEON
 1018 FORMAT(/,1X,E12.5,5X,'TIMEON',10X,'TOTAL TIME LASER IS TURNED ON')
      WRITE(6,1023)NPULSE
 1023 FORMAT(/,1X,E12.5,5X,'NPULSE',10X,'NUMBER OF LASER PULSES FIRED')
      RETURN
      END
```

5.4.3 (Continued)

PAGE 0001

TSOBJ.NADAPT.FORT
05/02/79 09:49:20

```
      SUBROUTINE NADAPT(NROW,NCOL,PROD,THOPTA,THGC,THOPTC,NCH,V,R,THN,Q,
     1ZASGA,ADLTA,ZASA,ZAMA,ADLTAS,ADLTAM,ADLTAB,ADLTAZ,TSLOT,MAAG,SNR,
     2AAE,DIVMIN,OVLAP,B,RESDIM,DRADIS,MAXNUP,TIMAVL,NRE,PRF,
     3/PHPEAK/,/NEPTOT/,/SN/,/BNDIV/,/ASC/,/NSPOT/,/EUM/)
C
      IMPLICIT REAL (A-Z)
C
C
      INTEGER I,J,KK,L,NROW,NCOL,COUNT
C
      DIMENSION THGC(NROW,NCOL),THOPTC(NROW,NCOL),NCH(NROW,NCOL),
     2ZASGA(NROW,NCOL),ADLTA(NROW,NCOL),ZASA(NROW,NCOL),ZAMA(NROW,NCOL),
     3ADLTAS(NROW,NCOL),ADLTAM(NROW,NCOL),ADLTAB(NROW,NCOL),
     4ADLTAZ(NROW,NCOL),V(NROW,NCOL),PHPEAK(NROW,NCOL),
     5NEPTOT(NROW,NCOL),SN(NROW,NCOL),
     6ASC(NROW,NCOL),R(NROW,NCOL),NSPOT(NROW,NCOL),FOM(NROW,NCOL),
     7N(NROW,NCOL),THN(NROW,NCOL)
C
      PI=2.*ARCOS(0.0)
      SNREQ=MAAG*SNR
      BNDIV=DIVMIN
      NEFM=0.
      NTSPOT=0.
      TFIRST=1.0
      COUNT=0
C     INITIALIZE VARIABLES AND READ OPTION FOR FILE 7 IN DSPOPN
C
      DO 100 J=1,NCOL
      DO 100 I=1,NROW
      ASC(I,J)=0.
      NSPOT(I,J)=0.
      IF(THOPTC(I,J).LT.0.)GO TO 100
   10 ASC(I,J)=R(I,J)*DIVMIN**2/COS(ZASGA(I,J)*PI/180.)*OVLAP*
     1(1.-OVLAP**2)**.5
C     USEFUL AREA OF SPOT FOR GIVEN RESOLUTION ELEMENT
   20 NSPOT(I,J)=AINT(AAE/ASC(I,J)+1.)
C     NUMBER OF SPOTS WITHIN RESOLUTION ELEMENT
   30 NTSPOT=NTSPOT+NSPOT(I,J)
C     TOTAL NUMBER OF SPOTS IN COVERAGE AREA
  100 CONTINUE
C
  110 TTOTAL=NTSPOT*RESDIM*(NTSPOT 1.)*DRADIS
  115 IF(TTOTAL.GE.TIMAVL)BNDIV=DIVMIN*(TTOTAL/TIMAVL)**.5)
C     CHECK TO SEE IF AREA CAN BE COVERED BY ONE TERMINAL
      ATBWF=BNDIV
      WRITE(6,1)
    1 FORMAT('1'//////40X,10('*'),'OUTPUT FROM DSPOPN',10('*'))
      DO 200 J=1,NCOL
      DO 200 I=1,NROW
      FOM(I,J)=0.0
      IF(ZASGA(I,J).GT.90.0)GO TO 200
      CALL DSPOPN(THOPTA,THGC(I,J),THOPTC(I,J),ATBWF,NCH(I,J),V(I,J),
     1R(I,J),THN(I,J),Q,ZASGA(I,J),ADLTA(I,J),ZASA(I,J),ZAMA(I,J),
     2ADLTAS(I,J),ADLTAM(I,J),ADLTAB(I,J),ADLTAZ(I,J),TSLOT,N(I,J),
     3TFIRST,PHPEAK(I,J),NEPTOT(I,J))
      COUNT=COUNT+1
      IF(COUNT.EQ.50)WRITE(6,1)
```

5.4.3 (Continued)

```
FSOBJ.NADAPT.FORT                                        PAGE 0002
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      IF(COUNT.EQ.50)COUNT=0
  990 WRITE (6,9990)(ASGA(I,J),PPPEAK(I,J),NEPTOT(I,J),I,J
 9990 FORMAT (1X,'ZASGA=',E12.5,10X,'PPPEAK=',E12.5,10X,'NEPTOT=',F12.5,
     2I24,'COORDINATES',2X,'I',I3,'J',I3,')'/)
      IFIRST=0.0
  120 SN(I,J)=PPPEAK(I,J)/NEPTOT(I,J)
C     SIGNAL TO NOISE RATIO FOR (I,J) ELEMENT
  130 FOM(I,J)=SN(I,J)/SNREQ
C     SIGNAL TO NOISE RECEIVED TO SIGNAL TO NOISE REQUIRED
  150 IF(FOM(I,J).GT.1.0)NFOM=NFOM+1
  200 CONTINUE
C
  300 AVL=NFOM/NNN
C     AVAILABLE COVERAGE AREA
      IF(TIMAVL-TTOTAL)400,400,450
  400 TIMEON=WARMUP+TIMAVL
      GO TO 500
  450 TIMEON=WARMUP+TTOTAL
C     TIME LASER IS ON
  500 NPULSE=TIMEON*PRF
C     NUMBER OF PULSES REQUIRED DURING OPERATION
      WRITE(6,1000)
 1000 FORMAT('1'/////59X,10('*'),'OUTPUT FROM NADAPT',10('*'))
 1130 CALL ARYRIT(25,NROW,NCOL,FOM)
 1010 CALL ARYRIT(27,NROW,NCOL,SSC)
 1020 CALL ARYRIT(20,NROW,NCOL,NSPOT)
      WRITE(6,1115)RMDIV
 1115 FORMAT(/1X,E12.5,5X,'RMDIV',11X,'MEAN DIVERGENCE')
      WRITE(6,1033)NTSPOT
 1033 FORMAT(/1X,E12.5,5X,'NTSPOT',10X,'TOTAL NUMBER OF SPOTS REQD')
      WRITE(6,1110)TTOTAL
 1110 FORMAT(/1X,E12.5,5X,'TTOTAL',10X,'TOTAL TIME NEEDED TO COVER ALL
     2AVAILABLE RESOLUTION ELEMENTS')
C
 1245 WRITE(6,1300)AVL
 1300 FORMAT(/1X,E12.5,5X,'AVL',13X,'FRACTION OF COVERAGE AREA THAT IS
     2AVAILABLE')
      WRITE(6,1400)TIMEON
 1400 FORMAT(/1X,E12.5,5X,'TIMEON',10X,'TOTAL TIME LASER IS TURNED ON')
      WRITE(6,1500)NPULSE
 1500 FORMAT(/1X,E12.5,5X,'NPULSE',10X,'NUMBER OF LASER PULSES FIRED')
      RETURN
      END
```

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ELECTRONIC SYSTEMS GROUP

5.4.3 (Continued)

ISD83.AAVRIT.FORT PAGE 0001
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```
      SUBROUTINE ARVRIT(INDEX,NROW,NCOL,/ARRAY/)
C     SUBROUTINE TO PRINT ARRAYS FOR OUTPUT
C
      IMPLICIT REAL (A-Z)
      INTEGER NCOL,NROW,INDEX,I,J,K,M,N,JEND,IEND
      DIMENSION ARRAY(NROW,NCOL)
C
   10 DO 3000 J=1,NCOL,10
C     MAXIMUM OF 10 COLUMNS PER PAGE
      JEND=J+9
      IF(JEND.GT.NCOL)JEND=NCOL
C     CHECK TO SEE IF LESS THAN 10 COLUMNS
C
   20 DO 3000 I=1,NROW,50
C     MAXIMUM OF 50 ROWS PER PAGE
      IEND=I+49
      IF(IEND.GT.NROW)IEND=NROW
C     CHECK TO SEE IF LESS THAN 50 ROWS
C
      GO TO(101,102,103,104,105,106,107,108,109,110,111,112,113,114,115,
     0116,117,118,119,120,121,122,123,124,125,126,127,128,129,130,1311,1
     INDEX
C     COMPUTED GO TO FOR PAGE LABEL
C
C
C     TITLE SECTION
C
  101 WRITE(6,1010)
 1010 FORMAT('1'/////66X,'THOPIC'/54X,'OPTICAL THICKNESS OF CLOUD')
      GO TO 2000
  102 WRITE(6,1020)
 1020 FORMAT('1'/////65X,'THGC'/52X,'GEOMETRICAL THICKNESS OF CLOUD')
      GO TO 2000
  103 WRITE(6,1030)
 1030 FORMAT('1'/////65X,'HCW'/49X,'DISTANCE,CLOUD BASE-WATER SURFACE')
      GO TO 2000
  104 WRITE(6,1040)
 1040 FORMAT('1'/////66X,'V'/54X,'SURFACE WIND SPEED (M/SEC)')
      GO TO 2000
  105 WRITE(6,1050)
 1050 FORMAT('1'/////65X,'ZPAR'/52X,'ZENITH PTING ANGLE OF RECEIVER')
      GO TO 2000
  106 WRITE(6,1060)
 1060 FORMAT('1'/////65X,'APAR'/50X,'AZIMUTHAL PTING ANGLE OF RECEIVER')
      GO TO 2000
  107 WRITE(6,1070)
 1070 FORMAT('1'/////65X,'ZASA'/56X,'SOLAR IN-AIR ZENITH ANGLES')
      GO TO 2000
  108 WRITE(6,1080)
 1080 FORMAT('1'/////65X,'ZAMA'/56X,'LUNAR IN-AIR ZENITH ANGLES')
      GO TO 2000
  109 WRITE(6,1090)
 1090 FORMAT('1'/////66X,'R'/45X,'RANGE FROM SATELLITE TO RESOLUTION ELE
     1MENTS')
      GO TO 2000
  110 WRITE(6,1100)
 1100 FORMAT('1'/////55X,'ZASGA'/56X,'SIGNAL IN-AIR ZENITH ANGLES')
```

5.4.3 (Continued)

PAGE 0002

ISOBJ.ARVEIT.FORT
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```
      GO TO 2000
  111 WRITE(6,1110)
 1110 FORMAT('1'/////66X,'XE'/56X,'SUBMARINE COORDINATES')
      GO TO 2000
  112 WRITE(6,1120)
 1120 FORMAT('1'/////66X,'YE'/56X,'SUBMARINE COORDINATES')
      GO TO 2000
  113 WRITE(6,1130)
 1130 FORMAT('1'/////66X,'ZE'/56X,'SUBMARINE COORDINATES')
      GO TO 2000
  114 WRITE(6,1140)
 1140 FORMAT('1'/////64X,'AZSGA'/55X,'AZIMUTHAL SIGNAL ANGLES')
      GO TO 2000
  115 WRITE(6,1150)
 1150 FORMAT('1'/////64X,'ZASGW'/52X,'SIGNAL IN-WATER ZENITH ANGLES')
      GO TO 2000
  116 WRITE(6,1160)
 1160 FORMAT('1'/////64X,'AZSUA'/56X,'AZIMUTHAL SOLAR ANGLES')
      GO TO 2000
  117 WRITE (6,1170)
 1170 FORMAT('1'/////65X,'ZASW'/53X,'SOLAR IN-WATER ZENITH ANGLES')
      GO TO 2000
  118 WRITE(6,1180)
 1180 FORMAT('1'/////64X,'AZMNA'/56X,'AZIMUTHAL LUNAR ANGLES')
      GO TO 2000
  119 WRITE(6,1190)
 1190 FORMAT('1'/////65X,'ZAMW'/53X,'LUNAR IN-WATER ZENITH ANGLES')
      GO TO 2000
  120 WRITE(6,1200)
 1200 FORMAT('1'/////64X,'ANGIA'/57X,'OFFSET ANGLE-SIGNAL')
      GO TO 2000
  121 WRITE(6,1210)
 1210 FORMAT('1'/////64X,'ANGIAS'/58X,'OFFSET ANGLE-SOLAR')
      GO TO 2000
  122 WRITE(6,1220)
 1220 FORMAT('1'/////64X,'ANGIAM'/58X,'OFFSET ANGLE-LUNAR')
      GO TO 2000
  123 WRITE(6,1230)
 1230 FORMAT('1'/////64X,'ANGIAB'/56X,'OFFSET ANGLE-BLUE SKY')
      GO TO 2000
  124 WRITE(6,1240)
 1240 FORMAT('1'/////64X,'ANGIAZ'/52X,'OFFSET ANGLE-STELLAR ZODIACAL')
      GO TO 2000
  125 WRITE(6,1250)
 1250 FORMAT('1'/////65X,'FOM'/53X,'RATIO OF S/N TO S/N REQUIRED')
      GO TO 2000
  126 WRITE(6,1260)
 1260 FORMAT('1'/////64X,'BMDIV'/59X,'BEAM DIVERGENCE')
      GO TO 2000
  127 WRITE(6,1270)
 1270 FORMAT('1'/////65X,'ASC'/56X,'AREA OF SQUARE IN SPOT')
      GO TO 2000
  128 WRITE(6,1280)
 1280 FORMAT('1'/////64X,'NSPOT'/48X,'NUMBER OF SPOTS IN RESOLUTION ELE
     $MENT')
      GO TO 2000
  129 WRITE(6,1290)
```

5.4.3 (Continued)

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                                                                   FTN03.ARYRIT.FORT        PAGE 0003
                                                                   05/02/79  09131107

 1290 FORMAT('1'/////65X,'TIME'/53X,'TIME PER RESOLUTION ELEMENT')          00001140
      GO TO 2000                                                            00001141
  130 WRITE(6,1300)                                                         00001142
 1300 FORMAT('1'////60X,'K'/55X,'DIFFUSE ATTENUATION COEFFICIENTS OF TH00001144
     1E WATER')                                                             00001145
      GO TO 2000                                                            00001146
  131 WRITE(6,1310)                                                         00001147
 1310 FORMAT('1'/////65X,'THH'/51X,'THICKNESS OF THE WATER LAYERS')         00001148
C                                                                           00001150
C                                                                           00001160
C     SECTION TO WRITE ARRAY                                                00001170
C                                                                           00001180
 2000 WRITE(6,2010)(N,N=J,JEND)                                             00001190
 2010 FORMAT(13X,10(I7,5X))                                                 00001200
      DO 3000 M=1,IEND                                                      00001210
      WRITE(6,2020)(M,(ARRAY(M,N),N=J,JEND))                                00001220
 2020 FORMAT(1X,I7,5X,10E12.5)                                              00001230
 3000 CONTINUE                                                              00001240
      RETURN                                                                00001250
      END                                                                   00001260
```

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5.4.3 (Continued)

TSOBJ.ESPOPN.FORT
05/02/79 15:30:55

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```
      SUBROUTINE ESPOPN(THOPTA,THGC,THOPTC,ATBUF,WCW,V,A,THW,Q,ZASGA,
     1DELTA,ZASA,ZAMA,ADLTAS,ADLTAM,ADLTAB,ADLTAZ,TSLUT,RANGE,IFIRST,
     1PROFAK,NFPTOT)
       IMPLICIT REAL(A-Z)
       INTEGER I,J,NPW,NTW
      NAMELIST/INPUT/ET,GANT,
     1COSACS,OMEGO,ACSCAT,ROEB,ANSWO,DEPR,ABVOV,
     1GAMB,DIAR,AS,LSR,AP,LMR,LOSR,AZR,SCATO,
     1DWAPT,KT,NOISFA,G,RESP,AL,ID,
     1NOISF,LDLR,RITOP2
C
      IF (IFIRST.EQ.0.0) GO TO 25
C     CHECK FOR FIRST PASS THROUGH SUBROUTINE: IF YES IFIRST=1.0
   10 READ(7,INPUT)
C     READ INPUT PARAMETERS INCLUDING UPDATES
C
      WRITE(6,15)ET,GANT,COSACS,OMEGO,ACSCAT,ROEB,ANSWO,DEPR,ABVOV,GAMB,
     1DIAR,AS,LSR,AM,LMR,LOSR,LZR,SCATO,DWAPT,KT,NOISFA,G,RESP,AL,ID,
     1NOISF,LDLR,RITOP2
   15 FORMAT(1X,E12.5)
   25 PI=2.0*ARCOS(0.0)
      QE=1.6E-19
      C=3.0E8
   30 TSGA=EXP(-THOPTA/COS(ZASGA*PI/180.))
C     CLEAR ATMOSPHERIC TRANSMISSION-SIGNAL
C     CALCULATION FOR OPTICAL THICKNESS OF CLOUD FOLLOWS.
C     PROGRAM WILL BRANCH TO HANDLE THICKNESS: THOPTC=0.,
C     0.LT.THOPTC.LT.10.AND THOPTC.GE.10.
C
   45 IF(THOPTC.LT.0.0) GO TO 5000
   90 IF(THOPTC-1.E-10) 2100,2100,91
   91 IF(THOPTC.GE.10.) GO TO 1100
C     **********
C     THIS SECTION WILL HANDLE CLOUD OPTICAL THICKNESS.GT.0.AND.LT.10.
C     ***** SIGNAL *****
C
C
      TEMP=(1.-.0059*THOPTC*1.65/(10.*(1.-COSACS)*1.42))
      TSGC=TEMP*(COS(ZASGA*PI/180.))**(G*1.)
C     CLOUD SIGNAL ENERGY TRANSMISSION
  105 TSGCW=1.
C     CLOUD TO WATER ENERGY TRANSMISSION
C     THIS SECTION CALCULATES SIGNAL ENERGY TRANSMISSION OF AIR-WATER
C     INTERFACE.
  110 IF(V.LT.0.0.OR.V.GT.15.0) GO TO 9009
  112 IF(ZASGA.LT.0.0.OR.ZASGA.GT.90.0) GO TO 9010
  115 TSGAW=DUALINT(V,ZASGA)
C     INTERPOLATING ON TABLE FOR DUALINT.
  120 TSGAWP=1.-1.2E-5*V**3.)
  121 IF(V.GT.9.)TSGAWP=1.-(1.2E-5*V**3.)*(1.225*V-.99)
  125 TSGAW=TSGAW*TSGAWP
C     SIGNAL ENERGY TRANSMISSION OF AIR-WATER INTERFACE
  130 SUM1=0.0
      DEPR=0.0
      SUM1=SUM1+KD*THW
  135 DEPR=DEPR+THW
      ZASGW=ARSIN(SIN(ZASGA*PI/180.)/NCEX)
```

5.4.3 (Continued)


```
  140 TSGW=EXP(-SUM1/COS(ZASGW))                                      00000580
C     SIGNAL WATER ENERGY TRANSMISSION 130-140                        00000590
C                                                                     00000600
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF SIGNAL RADIANCE   00000610
  150 FA=(.2956*ATBW/NOEX)**2                                         00000620
  152 FAW=.0103*.0103*V*2./(1.03*(100./PI))**2                        00000630
      TEMP2=ANSW*OSCAT*DEPH                                           00000640
  154 FW=TEMP2/COS(ZASGW)                                             00000650
  156 ARDWGS=SQRT(FA*FA+FW*FW)                                        00000660
  157 IF(ARDWGS.GT.50.2.OR.ARDWGS.LT.0.1) GO TO 9015                  00000670
  158 ARDWSG=INTTP(ARDWGS)                                            00000680
  160 PSG=CSINT2(ARLTA,ARDWSG,ARFOV)                                  00000690
C                                                                     00000700
C     THIS SECTION CALCULATES RECEIVED PULSE WIDTH AND SHAPE          00000710
C                                                                     00000720
  170 CPWC=0.0                                                        00000730
C     PULSE WIDTH DUE TO WATER PORTION OF PATH                        00000740
  172 CPWCW=2.*DEPH*TAN(ARFOV*PI/180.)*SIN(ZASGA*PI/180.)/C           00000750
C     ADDITIONAL PULSE WIDTH DUE TO CLOUD TO WATER PATH               00000760
  174 CPWW=(1.-COS(ARFOV*PI/180.))/COS(ARFOV*PI/180.)*DEPH*WNDEX/C    00000770
C     PULSE WIDTH AFTER EMERGING FROM CLOUD                           00000780
  180 TIPEAK=(CPWC+CPWCW+DPWW)/2.45                                   00000790
C                                                                     00000800
C     THIS SECTION CALCULATES TOTAL RECEIVED OPTICAL ENERGY PER PULSE 00000810
C                                                                     00000820
  190 ER=(((GANT/(PI*((ATBW*PI/180.)**2.)/4.)))*((PI*DIAR*DIAR/4.)*   00000830
     SGAMR/(RANGE*RANGE))*ET*TSGA*TSGC*TSGW*TSGCW*TSGAW*PSG           00000840
C     TOTAL RECEIVED OPTICAL ENERGY PER PULSE                         00000850
C     PW=ER*TT*EXP(-TT/TIPEAK)/TIPEAK**2.                             00000860
C     INSTANTANEOUS RECEIVED OPTICAL POWER                            00000870
  195 PRPEAK=ER*EXP(-1.)/TIPEAK                                       00000880
C     PEAK INSTANTANEOUS RECEIVED OPTICAL POWER                       00000890
C                                                                     00000900
C     *****NOISE*****                                                 00000910
C                      ***SOLAR***                                    00000920
  200 IF(LSD.LE.0.0) GO TO 299                                        00000930
  202 IF(ZASA.GT.90.0) GO TO 299                                      00000940
C                                                                     00000950
  205 TSBKA=EXP(-THKPTA/COS(ZASA*PI/180.))                            00000960
C     BACKGROUND CLEAR ATMOSPHERE ENERGY TRANSMISSION                 00000970
  207 TSC=TEMP*(COS(ZASA*PI/180.))**2                                 00000980
C     BACKGROUND CLOUD ENERGY TRANSMISSION                            00000990
  209 TBKCW=1.                                                        00001000
C     BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION                   00001010
C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR WATER  00001020
C     INTERFACE.                                                      00001030
  219 TSAWN=BWC(WV,ZASA)                                              00001040
C     INTERPOLATING ON TABLE FOR DOWNLINK.                            00001050
  225 TSAW=TSGAW*TSAWN                                                00001060
C     TOTAL BACKGROUND ENERGY TRANSMISSION IF AIR-WATER INTERFACE      00001070
      ZASW=ARSIN(SIN(ZASA*PI/180.)/WDEX)                              00001080
  240 TSW=EXP(-SUM1/COS(ZASW))                                        00001090
C     WATER ENERGY TRANSMISSION 230-240                               00001100
  250 LSD=LSD*TSBKA*TSC*TBKCW*TSAW*TSW                                00001110
C     AVERAGE BACKGROUND DUE TO SUNLIGHT                              00001120
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 260 270  00001130
  260 FAS=(AS/NOEX)**2.                                               00001140
```

5.4.3 (Continued)

ISG03.USPUFH.F001 PAGE 0003
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```
  202 FAWS=.01030.01030*V*2./(1.C3*(10C./P11)**2
  204 FWSQ=TEMP2/COS(ZASW)
  206 ARDWSA=SQRT(FWSQ*FAWS*FAS)
  209 IF(ARDWSA.GT.50.2.OR.ARDWSA.LT.C.)GO TO 9020
  210 ARDWAS=INTERP(ARDWCN)
  200 FNS=CSTRC2(AW TAS,ARDWAS,ARFOV)
C     FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW
  240 PBS=(SEC*GAMA*(PI*DIAR)**2.*RWOPT*FNS*(1.-COS(ARFOV*PI/180.))/2.
C     AVERAGE BACKGROUND POWER DUE TO SUNLIGHT
  255 GO TO 300
  299 PBS=C.0
C     NO SOLAR CONTRIBUTION
C                    ***LUNAR***
  300 IF(LMB.LT.0.0) GO TO 399
  302 IF(ZAMA.GT.90.0) GO TO 399
C
  305 THBWA=EXP(-THOPTA/COS(ZAMA*PI/180.))
C     BACKGROUND CLEAR ATMOSPHERE ENERGY TRANSMISSION
  307 THC=TEMP*(COS(ZAMA*PI/180.))**2
C     BACKGROUND CLOUD ENERGY TRANSMISSION
  309 TBKCW=1.
C     BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION
C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR WATER
C     INTERFACE.
  315 TRAWN=CNI(NRIV,ZAMA)
C     INTERPOLATING ON TABLE FOR OCEAN ION.
  325 TRAW=TRAWN*TSGAW
C     TOTAL BACKGROUND ENERGY TRANSMISSION OF AIR-WATER INTERFACE.
      ZAMW=APSIN(SIN(ZAMA*PI/180.)/NCE)
  340 TPW=EXP(-SUM/COS(ZAMW))
C     WATER ENERGY TRANSMISSION 330-340
  350 EPP=LMB*THBWA*THC*TBKCW*TRAW*TPW
C     AVERAGE BACKGROUND DUE TO MOONLIGHT
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 360-370
  360 FAN=(AM/NDEX)**2.
  362 FAWN=FAN
  364 FWMO=TEMP2/COS(ZAMW)
  366 ARDWCN=SQRT(FWMO*FAWN*FAN)
  369 IF(ARDWON.GT.50.2.OR.ARDWON.LT.C.) GO TO 9029
  370 ARDWAN=INTERP(ARDWON)
  380 FNM=CSTRB2(ADE TAN,ARDWAN,ARFOV)
C     FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW
  390 PPM=(NRO*GAMM*(PI*DIAR)**2.*RWOPT*FNM*(1.-COS(ARFOV*PI/180.))/2.
C     AVERAGE BACKGROUND POWER DUE TO MOONLIGHT
  395 GO TO 400
  399 PPM=C.0
C     NO LUNAR CONTRIBUTION
C                    ***BLUE SKY***
  400 IF(LBSF.LE.0.0) GO TO 499
  401 IF(THOPTA.LT.0.2.OR.THOPTA.GT.C.6) GO TO 9040
  402 IF(ZASA.GE.90.0) GO TO 499
  405 TBSBKA=E2(THOPTA)
C     BACKGROUND CLEAR ATMOSPHERIC ENERGY TRANSMISSION
  407 TBSC=.5*TEMP
C     BACKGROUND CLOUD ENERGY TRANSMISSION
  409 TBKCW=1.
C     BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION.
```

5.4.3 (Continued)

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ISOBJ.USPDPH.FORT
05/02/79 C5:38:58

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C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION UP AIR-WATER
C     INTERFACE.
  415 TOSAWN=0.01
  425 TOSAW=TOSAWN*TSGAWP
  440 TOSW=EXP(-SUM1)
C     WATER ENERGY TRANSMISSION 430-440
  450 LOSP=LOSP*TOSWA*TOSC*TBKCW*TOSAW*TOSW
C     AVERAGE BACKGROUND DUE TO BLUE SKY
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 460-470
  460 FABS=33.0**2.
  462 FAWBS=0.0
  464 FWASO=TEMP2
  466 ARGWGN=SQRT(FWASO*FAWBS*FABS)
  468 IF(ARGWGN.GT.50.2.OR.ARGWGN.LT.6.0) GO TO 9030
  470 ARGWNB=INTERP(ARGWGN)
  480 FWAS=CSTRB2(ARGTAB,ARGWNB,ARFOV)
C     FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW
  490 PBBS=LOSP*GAMR*(PI*DIAR)**2*OMEGP*FWAS*(1.-COS(ARFOV*PI/180.))/2.
C     AVERAGE BACKGROUND POWER DUE TO BLUE SKY
  495 GO TO 500
  499 PBBS=0.0
C     NO BLUE SKY CONTRIBUTION
C                    ***STELLAR/ZODIACAL LIGHT***
  500 IF(LZN.LT.0.01) GO TO 599
  501 IF(THOPTA.LT.0.2.OR.THOPTA.GT.6.0) GO TO 9040
  505 TZOHA=TZ(THOPTA)
C     BACKGROUND CLEAR ATMOSPHERIC ENERGY TRANSMISSION
  507 TZC=.5*TEMP
C     BACKGROUND CLOUD ENERGY TRANSMISSION
  509 TBKCW=1.
C     BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION
C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION UP AIR-WATER
C     INTERFACE.
  515 TZAWN=0.01
  525 TZAW=TZAWN*TSGAWP
  540 TZW=EXP(-SUM1)
C     WATER ENERGY TRANSMISSION 530 540
  550 LZW=LZ*TZOHA*TZC*TBKCW*TZAW*TZW
C     AVERAGE BACKGROUND DUE TO STELLAR/ZODIACAL LIGHT
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 560-570
  560 FAZ=33.0**2.
  562 FAWZ=0.0
  564 FWZO=TEMP2
  566 ARGWGN=SQRT(FWZO*FAWZ*FAZ)
  569 IF(ARGWGN.GT.50.2.OR.ARGWGN.LT.6.0) GO TO 9035
  570 ARGWNZ=INTERP(ARGWGN)
  580 FWZ=CSTRB2(ARGTAB,ARGWNZ,ARFOV)
C     FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW
  590 PBZ=LZW*GAMR*(PI*DIAR)**2.*OMEGP*FWZ*(1.-COS(ARFOV*PI/180.))/2.
C     AVERAGE BACKGROUND POWER DUE TO STELLAR/ZODIACAL LIGHT
  595 GO TO 600
  599 PBZ=0.0
C     NO STELLAR/ZODIACAL LIGHT CONTRIBUTION
C                    ***BIOLUMINESCENCE***
  600 PBBL=(LBLP*GAMR*PI*OMEGPT*(DIAR**2.))/4.
      GO TO 700
C     SUM OF THE AVERAGE BACKGROUND POWERS.
```

5.4.3 (Continued)

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TSUBJ.OSPDPH.FGDI
05/02/75 CS130156

```
C
C
C     THIS SECTION WILL HANDLE CLOUD OPTICAL THICKNESS.GE.10.
C     ***** SIGNAL *****
C
C
 1100 NUM3=1.69-0.5513*(ZASGA*PI/180.)+2.7173*(ZASGA*PI/180.)**2-6.9664*
     1((ZASGA*PI/180.)**3)+7.1446*(ZASGA*PI/180.)**4-3.0267*(ZASGA*PI/180.
     1)**5+0.6155*(ZASGA*PI/180.)**6
C
      TP3=1./(THOPTC*(1.-COSACS)+1.42)*2.0SQRT(3.*(1.-COSACS)*(1.-
     2OMEGO))*(THOPTC+1.42/(1.-COSACS))*EXP(-(SQRT(3.*(1.-COSACS)*(1.-
     3OMEGO))*(THOPTC+1.42/(1.-COSACS)))/(1.-EXP(-2.*SQRT(3.*(1.-
     4COSACS)*(1.-OMEGO))*(THOPTC+1.42/(1.-COSACS))))
C
      TMP3=NUM3*TP3
      TSGC=TMP3*(COS(ZASGA*PI/180.))**C
C     CLOUD SIGNAL ENERGY TRANSMISSION
 1105 TSGCD=1./((1.+(HCU/(RANGE*ATAN(FOPI/180./2.))**2.)
C     CLOUD TO WATER ENERGY TRANSMISSION
C     THIS SECTION CALCULATES SIGNAL ENERGY TRANSMISSION OF AIR-WATER
C     INTERFACE.
 1110 IF(V.LT.0.0.OR.V.GT.15.6) GO TO 5005
 1112 IF(ZASGA.LT.0.0.OR.ZASGA.GT.90.0) GO TO 9010
 1114 TSGAW=0.03
C     INTERPOLATING ON TABLE FOR OUWALING.
 1120 TSGAWF=1.-(1.2E-5*V**3.)
 1121 IF(V.GT.9.)TSGAWF=1.-((1.2E-5*V**3.)*(1.225*V-.99)
 1125 TSGAW=TSGAW*TSGAWF
C     SIGNAL ENERGY TRANSMISSION OF AIR-WATER INTERFACE
 1130 SUM1=0.0
      DEPR=0.0
      SUM1=SUM1+KOTHW
 1135 DEPR=DEPR+INW
 1140 TSGW=TYP1-SUM11
C     SIGNAL WATER ENERGY TRANSMISSION 1130-1140
C
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF SIGNAL RADIANCE
 1150 FA=33.0**2.
 1152 FAW=0.0
      TEMP2=ANSWO*SCATO*DEPR
 1154 FW=TEMP2
 1156 ARDWOS=SQRT(FA+FAW*FW)
 1157 IF(ARDWOS.GT.58.2.OR.ARDWOS.LT.0.) GO TO 9015
 1158 ARDWSG=INTERP(ARDWCS)
 1160 FSG=CSTRB2(ADELTA,ARDWSG,ARFOV)
C
C     THIS SECTION CALCULATES RECEIVED PULSE WIDTH AND SHAPE
C
 1170 DPWC=THWC/(C*(.3/OMEGO/THOPTC/((ACSCAT*PI/180.)**2)*((1.+2.25*OMEGO
     9*THOPTC*((ACSCAT*PI/180.)**2))**1.5-1.)-1.)
C     PULSE WIDTH DUE TO WATER PORTION OF PATH
 1172 DPWCW=0.0
C     ADDITIONAL PULSE WIDTH DUE TO CLOUD TO WATER PATH
 1174 DPWW=((1.-COS(ARFOV*PI/180.))/(COS(ARFOV*PI/180.))*DEPR*NDEX/C
C     PULSE WIDTH AFTER EMERGING FROM CLOUD
 1180 TIPCW=(DPWC+DPWCW+DPWW)/2.45
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5.4.3 (Continued)

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TSUBJ.DSPDPR.FORT
05/02/75 CSTRIJ58

```
C
C     THIS SECTION CALCULATES TOTAL RECEIVED OPTICAL ENERGY PER PULSE
C
 1190 ER=(ETTOGAMI/(PI*((ATOBS*FOV)/100.)**2.)/4.))*(PI*ULAR*ULAR/4.)*
     &GAMB/(RANGE*RANGE))*TSGA*TSGC*TSGW*TSGCB*TSGAW*FSW
C     TOTAL RECEIVED OPTICAL ENERGY PER PULSE
C     PW=(ER*T1*EXP(-T1/T1PEAK)/(T1PEAK**2.
C     INSTANTANEOUS RECEIVED OPTICAL POWER
 1195 PRPEAK=(ER*EXP(-1.)/T1PEAK
C     PEAK INSTANTANEOUS RECEIVED OPTICAL POWER
C
C     *****NOISE*****
C                   ***SCLAR***
 1200 IF(LSR.LE.0.0) GO TO 1299
 1202 IF(ZASA.GT.90.0) GO TO 1299
C
 1205 TSBKA=EXP(-THOPTA/COS(ZASA*PI/180.))
C     BACKGROUND CLEAR ATMOSPHERE ENERGY TRANSMISSION
      NUM3=1.69-0.5513*(ZASA*PI/180.)+2.7173*(ZASA*PI/180.)**2-4.9866*
     &(ZASA*PI/180.)**3+7.1446*(ZASA*PI/180.)**4-3.4249*(ZASA*PI/180.
     &)**5+0.6155*(ZASA*PI/180.)**6
      TPP3=NUM3*TP3
 1207 TSC=TPP3*(COS(ZASA*PI/180.))
C     BACKGROUND CLOUD ENERGY TRANSMISSION
 1209 TBKCW=1.
C     BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION
C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION UP AIR WATER
C     INTERFACE.
 1229 TSAW=TSGAW
C     TOTAL BACKGROUND ENERGY TRANSMISSION OF AIR-WATER INTERFACE
 1240 TSW=TSGW
C     WATER ENERGY TRANSMISSION 1230-1240
 1250 LSP=LSR*TSBKA*TSC*TBKCW*TSAW*TSW
C     AVERAGE BACKGROUND DUE TO SUNLIGHT
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 1260 1270
 1260 FAS=FA
 1262 FANS=0.0
 1264 FWSO=TEMP2
 1266 ARDWCR=ARDWBS
 1270 ARDWNS=ARDWSG
 1280 FRS=FSG
C     FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW
 1290 PRS=LSP*GAMR*(PI*DIAR)**2.*BWOPT*FRS*(1.-COS(AMFOV*PI/180.))/2.
C     AVERAGE BACKGROUND POWER DUE TO SUNLIGHT
 1295 GO TO 1300
 1299 PRS=0.0
C     NO SOLAR CONTRIBUTION
C                   ***LUNAR***
 1300 IF(LMR.LE.0.0) GO TO 1395
 1302 IF(ZAMA.GT.90.0) GO TO 1399
C
 1305 TMBKA=EXP(-THOPTA/COS(ZAMA*PI/180.))
C     BACKGROUND CLEAR ATMOSPHERE ENERGY TRANSMISSION
      NUM3=1.69-0.5513*(ZAMA*PI/180.)+2.7173*(ZAMA*PI/180.)**2-4.9866*
     &(ZAMA*PI/180.)**3+7.1446*(ZAMA*PI/180.)**4-3.4249*(ZAMA*PI/180.
     &)**5+0.6155*(ZAMA*PI/180.)**6
      TPP3=NUM3*TP3
```

GTE SYLVANIA
ELECTRONIC SYSTEMS GROUP
WESTERN DIVISION

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ISOBJ.OSPOPR.FORT
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 1307 TPC=TMP3*(COS(ZANA*PI/180.))                                     00003430
C       BACKGROUND CLOUD ENERGY TRANSMISSION                             00003440
 1309 TBKCW=1.                                                         00003450
C       BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION                    00003460
C       THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR WATER   00003470
C       INTERFACE.                                                       00003480
 1325 TMAW=TSGAW                                                       00003490
C       TOTAL BACKGROUND ENERGY TRANSMISSION OF AIR-WATER INTERFACE.     00003500
 1340 TMW=TSGW                                                         00003510
C       WATER ENERGY TRANSMISSION 1330-1340                              00003520
 1350 EMR=EMR*TMBKA*TMC*TBKCW*TMAW*TMW                                 00003530
C       AVERAGE BACKGROUND DUE TO MOONLIGHT                              00003540
C       THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 1360-1370 00003550
 1360 FAM=FA                                                           00003560
 1362 FAMW=0.0                                                         00003570
 1364 FWMO=TEMP2                                                       00003580
 1366 ARDWCM=ARDWOS                                                    00003590
 1370 ARDWAM=ARDWSG                                                    00003600
 1380 FMM=FSG                                                          00003610
C       FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW00003620
 1390 PRM=EMR*GAMR*(PI*DIAR)**2.*BWOPT*FMM*(1.-COS(ARFOV*PI/180.))/2.  00003630
C       AVERAGE BACKGROUND POWER DUE TO MOONLIGHT                        00003640
 1395 GO TO 1400                                                       00003650
 1399 PRM=0.0                                                          00003660
C       NO LUNAR CONTRIBUTION                                            00003670
C                     ***BLUE SKY***                                     00003680
 1400 IF(LOSA.LE.0.0) GO TO 1499                                       00003690
 1401 IF(IHOPTA.LT.0.2.OR.IHOPTA.GT.0.6) GO TO 9040                    00003700
 1402 IF(ZASA.GE.90.0) GO TO 1499                                      00003710
 1405 TBSBKA=E2(IHOPTA)                                                00003720
C       BACKGROUND CLEAR ATMOSPHERIC ENERGY TRANSMISSION                 00003730
 1407 TBSC=2.*TP3*1.69/3.                                              00003740
C       BACKGROUND CLOUD ENERGY TRANSMISSION                             00003750
 1409 TBKCW=1.                                                         00003760
C       BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION.                   00003770
C       THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR-WATER   00003780
C       INTERFACE.                                                       00003790
 1425 TBSAW=TSGAW                                                      00003800
 1440 TBSW=TSGW                                                        00003810
C       WATER ENERGY TRANSMISSION 1430-1440                              00003820
 1450 LBSR=LBSR*TBSBKA*TBSC*TBKCW*TBSAW*TBSW                           00003830
C       AVERAGE BACKGROUND DUE TO BLUE SKY                               00003840
C       THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 1460-1470 00003850
 1460 FABS=FA                                                          00003860
 1462 FAWBS=0.0                                                        00003870
 1464 FWBSC=TEMP2                                                      00003880
 1466 ARDWCN=ARDWOS                                                    00003890
 1470 ARDWAB=ARDWSG                                                    00003900
 1480 FNBS=FSG                                                         00003910
C       FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW00003920
 1490 PRBS=LBSR*GAMR*(PI*DIAR)**2*BWOPT*FNBS*(1.-COS(ARFOV*PI/180.))/2. 00003930
C       AVERAGE BACKGROUND POWER DUE TO BLUE SKY                         00003940
 1495 GO TO 1500                                                       00003950
 1499 PRBS=0.0                                                         00003960
C       NO BLUE SKY CONTRIBUTION                                         00003970
C                     ***STELLAR/ZODIACAL LIGHT***                       00003980
 1500 IF(LZ.LE.0.0) GO TO 1595                                         00003990
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5.4.3 (Continued)

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TSG03.DSPDPR.LGHT                                    PAGE 0006
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 1561 IF(THMPTA.LT.0.7.OR.THMPTA.GT.C.2) GO TO 9063              00004000
 1505 T7MA=-1.2(THMPTA)                                           00004010
C     BACKGROUND CLEAR ATMOSPHERIC ENERGY TRANSMISSION            00004020
 1507 T7C=7.0*PTPI.A97).                                          00004030
C     BACKGROUND CLOUD ENERGY TRANSMISSION                        00004040
 1509 TPPCW=1.                                                    00004050
C     BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION               00004060
C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR WATER 00004070
C     INTERFACE.                                                  00004080
 1525 T7AW=TSGAW                                                  00004090
 1540 T7W=TSGW                                                    00004100
C     WATER ENERGY TRANSMISSION 1530-1540                         00004110
 1550 T7P=T7A*T7BA*T7C*T7BC*T7AW*T7W                              00004120
C     AVERAGE BACKGROUND DUE TO STELLAR/ZODIACAL LIGHT            00004130
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 1560-1570 00004140
 1560 FZZ=FA                                                      00004150
 1562 FAWZ=0.0                                                    00004160
 1564 FWZO=TEMP2                                                  00004170
 1576 ARONWZ=ARCWOS                                               00004180
 1580 FNZ=FSL                                                     00004190
C     FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW00004200
 1590 PRZ=L7*OGAMMA*EP(ODIAR)**2*OMEGA*P7*FNZ*(1.-COS(APFOV*PI/180.))/2. 00004210
C     AVERAGE BACKGROUND POWER DUE TO STELLAR/ZODIACAL LIGHT      00004220
 1595 GO TO 1600                                                  00004230
 1555 PRZ=0.0                                                     00004240
C     NO STELLAR/ZODIACAL LIGHT CONTRIBUTION                      00004250
C                     ***BIOLUMINESCENCE***                       00004260
 1600 PBAL=(LBL*OGAMMA*PI*OMEGA*T7*(DIAR**2.))/4.                 00004270
      GO TO 700                                                   00004280
C     SUM OF THE AVERAGE BACKGROUND POWERS.                       00004290
C                                                                 00004300
C                                                                 00004310
C     THIS SECTION WILL HANDLE CLOUD OPTICAL THICKNESS.EQ.0.      00004320
C     ***** SIGNAL *****                                          00004330
C                                                                 00004340
C                                                                 00004350
 2100 TSGC=COS(ZASGA*PI/180.)**0                                  00004360
C     CLOUD SIGNAL ENERGY TRANSMISSION                            00004370
 2105 TSGCW=1.                                                    00004380
C     CLOUD TO WATER ENERGY TRANSMISSION                          00004390
C     THIS SECTION CALCULATES SIGNAL ENERGY TRANSMISSION OF AIR-WATER 00004400
C     INTERFACE.                                                  00004410
 2110 IF(V.LT.0.0.OR.V.GT.15.0) GO TO 9009                        00004420
 2112 IF(ZASGA.LT.0.0.OR.ZASGA.GT.90.0) GO TO 9010                00004430
 2114 TSGAWN=DNLINE(V,ZASGA)                                      00004440
C     INTERPOLATING ON TABLE FOR DOWNLINK.                        00004450
 2120 TSGAWP=1.-1.3E-5*V**3.5                                     00004460
 2121 IF(V.GT.9.)TSGAWP=1.-(1.2E-5*V**3.5)*(.225*V-.99)           00004470
 2125 TSGAW=TSGAWN*TSGAWP                                         00004480
C     SIGNAL ENERGY TRANSMISSION OF AIR-WATER INTERFACE           00004490
 2130 SUM1=0.0                                                    00004500
      DEPR=0.0                                                    00004510
      SUM1=SUM1+K*THW                                             00004520
 2135 DEPR=DEPR+THW                                               00004530
      ZASGW=ARSIN(SIN(ZASGA*PI/180.)/NCEX)                        00004540
 2140 TSGW=EXP(-SUM1/COS(ZASGW))                                  00004550
C     SIGNAL WATER ENERGY TRANSMISSION 2130-2140                  00004560
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5.4.3 (Continued)

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TSUBJ.DSPOPP.FCRT
05/02/75 C9130158

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C                                                                    00004570
C      THIS SECTION CALCULATES WATER DISTRIBUTION OF SIGNAL RADIANCE 00004580
 2150 FA=(.2960*ATDWF/NDEX)**2                                       00004590
 2152 FAW=.01030+.01030*V**2./(1.0*(100./PI))**2                     00004600
      TEMP2=ANSWBO*SCATO*DEPTH                                       00004610
 2154 FW=TEMP2/COS(ZASGW)                                            00004620
 2156 ARDWOS=SQRT(FA+FAW+FW)                                         00004630
 2157 IF(ARDWOS.GT.50.2.OR.ARDWOS.LT.C.) GO TO 9015                   00004640
 2158 ARDWSG=INTERP(ARDWCS)                                          00004650
 2160 FSG=CSIMP2(ADLTA,ARDWSG,ARFOV)                                 00004660
C                                                                    00004670
C      THIS SECTION CALCULATES RECEIVED PULSE WIDTH AND SHAPE        00004680
C                                                                    00004690
 2170 DPWC=0.0                                                       00004700
C      PULSE WIDTH DUE TO WATER PORTION OF PATH                      00004710
 2172 DPWCW=2.*DEPTH*TAN(ARFOV*PI/100.)*SIN(ZASGA*PI/100.)/C         00004720
C      ADDITIONAL PULSE WIDTH DUE TO CLOUD TO WATER PATH             00004730
 2174 DPWW=(1.-COS(ARFOV*PI/100.))/COS(ARFOV*PI/100.)*DEPTH*NDEX/C   00004740
C      PULSE WIDTH AFTER EMERGING FROM CLOUD                         00004750
 2180 TIPEAK=(DPWC+DPWCW+DPWW)/2.45                                  00004760
C                                                                    00004770
C      THIS SECTION CALCULATES TOTAL RECEIVED OPTICAL ENERGY PER PULSE 00004780
C                                                                    00004790
 2190 ER=(EE*GAMT/(PI*((ALTDW*PI/180.)**2./4.))*(PI*DIAMR*DIAR/4.)*  00004800
     $GAMR/(RANGE*RANGE))*TSGA*TSGC*TSGW*TSGCW*TSGAW*FSG             00004810
C      TOTAL RECEIVED OPTICAL ENERGY PER PULSE                       00004820
C      PR=ER*T*EXP(-T/TIPEAK)/TIPEAK**2.                             00004830
C      INSTANTANEOUS RECEIVED OPTICAL POWER                          00004840
 2195 PRPEAK=ER*EXP(-1.)/TIPEAK                                      00004850
C      PEAK INSTANTANEOUS RECEIVED OPTICAL POWER                     00004860
C                                                                    00004870
C      *****NOISE*****                                               00004880
C                    ***SOLAR***                                     00004890
 2202 IF(ZASA.GT.90.0) GO TO 2295                                    00004900
C                                                                    00004910
 2205 TSBAA=EXP(-THOPTA/COS(ZASA*PI/180.))                           00004920
C      BACKGROUND CLEAR ATMOSPHERE ENERGY TRANSMISSION               00004930
 2207 TSC=COS(ZASA*PI/180.)                                          00004940
C      BACKGROUND CLOUD ENERGY TRANSMISSION.                         00004950
 2209 TBKCW=1.                                                       00004960
C      BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION                 00004970
C      THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR WATER 00004980
C      INTERFACE.                                                    00004990
 2215 TSAWW=CRLIN(IV,ZASA)                                           00005000
C      INTERPOLATING ON TABLE PER DUNNLINE.                          00005010
 2225 TSAW=TSAWW*TSGAW                                               00005020
C      TOTAL BACKGROUND ENERGY TRANSMISSION IF AIR-WATER INTERFACE    00005030
      ZASW=ARSIN(SIN(ZASA*PI/180.)/NDEX)                             00005040
 2240 TSW=EXP(-SUM/COS(ZASW))                                        00005050
C      WATER ENERGY TRANSMISSION 2230-2240                           00005060
 2250 ESR=ESA*TSBAA*TSC*TBKCW*TSAW*TSW                               00005070
C      AVERAGE BACKGROUND DUE TO SUNLIGHT                            00005080
C      THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 2260-2270 00005090
 2260 FAS=(AS/NDEX)**2.                                              00005100
 2262 FAWS=FAW                                                       00005110
 2264 FWSO=TEMP2/COS(ZASW)                                           00005120
 2266 ARDWSN=SQRT(FWSO+FAWS+FAS)                                     00005130
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5.4.3 (Continued)


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 2269 IF(ABDWON.GT.90.2.OR.ABDWON.LT.0.)GO TO 9020
 2270 ABDWNS=INTERP(ABDWON)
 2280 FNS=CSTRC2(ABLTAS,ABDWNS,ABFOV)
C     FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW
 2290 PNS=(SPECAMB*(PI*DIAR)**2.*RHOPT*FNS*(1.-COS(ABFOV*PI/180.))/2.
C     AVERAGE BACKGROUND POWER DUE TO SUNLIGHT
 2295 GO TO 2300
 2299 PNS=0.0
C     NO SOLAR CONTRIBUTION
C                    ***LUNAR***
 2300 IF(LNS.LT.0.0) GO TO 2355
 2302 IF(ZANA.GT.90.0) GO TO 2399
C
 2305 TNBKA=EXP(-THOPTA/COS(ZANA*PI/180.))
C     BACKGROUND CLEAR ATMOSPHERE ENERGY TRANSMISSION
 2307 TNC=COS(ZANA*PI/180.)
C     BACKGROUND CLOUD ENERGY TRANSMISSION
 2309 TNCW=1.
C     BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION
C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR WATER
C     INTERFACE.
 2315 TNAWN=BNLIN(V,ZANA)
C     INTERPOLATING ON TABLE PER DCWALTNE.
 2325 TNAW=TNAWN*TSGAW
C     TOTAL BACKGROUND ENERGY TRANSMISSION OF AIR-WATER INTERFACE.
      ZANW=ARSIN(SIN(ZANA*PI/180.)/NDEX)
 2340 TNW=EXP(-SWN)/COS(ZANW))
C     WATER ENERGY TRANSMISSION 2330-2340
 2350 TNN=CNT*TNBKA*TNC*TNBCW*TNAW*TNW
C     AVERAGE BACKGROUND DUE TO MOONLIGHT
C     THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 2360-2370
 2360 FAM=(AM/NDEX)**2.
 2362 FAMP=FAM
 2366 FUNO=TEMP2/COS(ZANW)
 2368 ABDWON=SQRT(FUNO*FAWN*FAMT)
 2369 IF(ABDWON.GT.90.2.OR.ABDWON.LT.0.) GO TO 9025
 2370 ABDWNN=INTERP(ABDWON)
 2380 FNN=CSTRC2(ABLTAN,ABDWNN,ABFOV)
C     FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW
 2390 PNM=LNM*GAMM*(PI*DIAR)**2.*RHOPT*FNM*(1.-COS(ABFOV*PI/180.))/2.
C     AVERAGE BACKGROUND POWER DUE TO MOONLIGHT
 2395 GO TO 2400
 2399 PNM=0.0
C     NO LUNAR CONTRIBUTION
C                    ***BLUE SKY***
 2400 IF(LBSA.LE.0.0) GO TO 2499
 2401 IF(THOPTA.LT.0.2.OR.THOPTA.GT.8.0) GO TO 9040
 2402 IF(ZASA.GE.90.0) GC TO 2499
 2405 TBSBKA=E2(THOPTA)
C     BACKGROUND CLEAR ATMOSPHERIC ENERGY TRANSMISSION
 2407 TBSC=1.
C     BACKGROUND CLOUD ENERGY TRANSMISSION
 2409 TBSCW=1.
C     BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION.
C     THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR-WATER
C     INTERFACE.
 2419 IF(ZASA=0.0)
```

5.4.3 (Continued)

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```
 2625 TOSAW=TOSAWN*ISGAMF                                                   00005710
 2640 TOSW=EXP(-SUM1)                                                       00005720
C       WATER ENERGY TRANSMISSION 2630-2640                                 00005730
 2650 TOSD=LOSR*TOSAWA*TOSC*TOBC*TOSW*TOSAB*TOSW                            00005740
C       AVERAGE BACKGROUND DUE TO BLUE SKY                                  00005750
C       THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 2660-2670    00005760
 2660 FABS=33.0**2.                                                         00005770
 2662 FAWBS=0.0                                                             00005780
 2664 FWBSQ=TEMP2                                                           00005790
 2666 ARDWGN=SQRT(FWBSQ+FAWBS*FABS)                                         00005800
 2669 IF(ARDWGN.GT.58.2.OR.ARDWGN.LT.0.0) GO TO 9030                        00005810
 2670 ARDWNB=INTERP(ARDWGN)                                                 00005820
 2680 FNBS=DSTRB2(ABLTAB,ARDWNB,ARFOV)                                      00005830
C       FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW  00005840
 2690 PNBS=LOSR*SGAMB*(PI*DIAM)**2*WOPI*FNBS*(1.-COS(ARFOV*PI/180.))/2.     00005850
C       AVERAGE BACKGROUND POWER DUE TO BLUE SKY                            00005860
 2695 GO TO 2500                                                            00005870
 2699 PNBS=0.0                                                              00005880
C       NO BLUE SKY CONTRIBUTION                                            00005890
C                   ***STELLAR/ZODIACAL LIGHT***                            00005900
 2500 IF(LZZ.LE.0.0) GO TO 2595                                             00005910
 2501 IF(INOPTA.LT.0.2.OR.INOPTA.GT.0.0) GO TO 9040                         00005920
 2505 TZBC=EXP(TZTINOPTA)                                                   00005930
C       BACKGROUND CLEAR ATMOSPHERIC ENERGY TRANSMISSION                     00005940
 2507 TZC=1.                                                                00005950
C       BACKGROUND CLOUD ENERGY TRANSMISSION                                00005960
 2509 TZBCW=1.                                                              00005970
C       BACKGROUND CLOUD TO WATER ENERGY TRANSMISSION                       00005980
C       THIS SECTION CALCULATES NOISE ENERGY TRANSMISSION OF AIR-WATER      00005990
C       INTERFACE.                                                          00006000
 2515 TZAWB=0.03                                                            00006010
 2525 TZAW=TZAWN*ISGAMF                                                     00006020
 2540 TZW=EXP(-SUM1)                                                        00006030
C       WATER ENERGY TRANSMISSION 2530-2540                                 00006040
 2550 TZN=LZZ*TZ*TZBA*TZC*TZBC*TZAW*TZAB*TZW                                00006050
C       AVERAGE BACKGROUND DUE TO STELLAR/ZODIACAL LIGHT                    00006060
C       THIS SECTION CALCULATES WATER DISTRIBUTION OF RADIANCE 2560-2570    00006070
 2560 FAZ=33.0**2.                                                          00006080
 2562 FAWZ=0.0                                                              00006090
 2564 FWZQ=TEMP2                                                            00006100
 2566 ARDWGN=SQRT(FWZQ+FAWZ*FAZ)                                            00006110
 2569 IF(ARDWGN.GT.58.2.OR.ARDWGN.LT.0.0) GO TO 9035                        00006120
 2570 ARDWNZ=INTERP(ARDWGN)                                                 00006130
 2580 FNZ=DSTRB2(ABLTAZ,ARDWNZ,ARFOV)                                       00006140
C       FRACTION OF INCIDENT RADIANCE SOURCE WITHIN RECEIVER FIELD OF VIEW  00006150
 2590 PNZ=LZZ*SGAMB*(PI*DIAM)**2*WOPI*FNZ*(1.-COS(ARFOV*PI/180.))/2.        00006160
C       AVERAGE BACKGROUND POWER DUE TO STELLAR/ZODIACAL LIGHT              00006170
 2595 GO TO 2600                                                            00006180
 2599 PNZ=0.0                                                               00006190
C       NO STELLAR/ZODIACAL LIGHT CONTRIBUTION                              00006200
C                   ***BIOLUMINESCENCE***                                   00006210
 2600 PNBL=(LBL*SGAMB*PI*WOPI*(DIAM)**2.)/4.                                00006220
C       CALCULATIONS FOR ALL INOPTC CONVERGE HERE.                          00006230
  700 PNTOT=PNS+PNM+PNBS+PNZ+PNBL                                           00006240
C       SUM OF THE AVERAGE BACKGROUND POWERS.                               00006250
  800 BW=0.4/(2.45*TIPEAK)                                                  00006260
C       ELECTRICAL DETECTION BANDWIDTH                                      00006270
```

5.4.3 (Continued)

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```
C
  050 1012.650T3PEAK-TSLOT)510.911.000
  060 WRITE(6.0611)
  061 FORMAT(1X.10('*').'LASER PULSE WIDTH IS GREATER THAN SLOT WIDTH FO
     1R COORDINATES GIVEN ON FOLLOWING LINE'.10('*'))
C
C
C
C      THIS SECTION CALCULATES TOTAL NOISE EQUIVALENT (OPTICAL) POWER DUE
C      TO ALL SOURCES.
C
  910 NEPSB=SQRT(2.*Q*POWE*NOISF*PB(OT))/RESP)
C      NOISE EQ. OPTICAL POWER DUE TO SHOT NOISE GENERATED BY BACKGROUND.
C
  920 NEPTH=SQRT(4.*KT*POWE*NOISFA/(RL*1G*RESP)**2.))
C      NOISE EQ. OPTICAL POWER DUE TO THERMAL OF AMPLIFIER NOISE.
C
  930 NEPID=SQRT(2.*Q*POWE*NOISF*ID/RESP)
C      NOISE EQ. OPTICAL POWER DUE TO PHOTO-DETECTOR DARK CURRENT.
C
  940 NEPSS=SQRT(2.*Q*POWE*NOISF*PPEAK/RESP)
C      NOISE EQ. OPTICAL POWER DUE TO SHOT NOISE GENERATED BY SIGNAL.
C
  950 NEPTOT=SQRT(NEPTH**2.+NEPID**2.+NEPSS**2.+NEPSB**2.)
C      TOTAL NOISE EQUIVALENT OPTICAL POWER DUE TO ALL SOURCES.
C
  960 IF(RITOP2.EQ.0.0)GO TO 9999
C      RITOP2 DETERMINES WHETHER TO PRINT INTERMEDIATE CALCULATIONS
C      ***********OUTPUT*************
C
       WRITE(6.0002)
 0002 FORMAT(///30X.'OUTPUT FOR SIGNAL SECTION'//)
       WRITE(6.0030)TSGA
 0030 FORMAT(1X.E12.5.5X.'TSGA'.12X.'CLEAR ATMOSPHERIC TRANS')
       WRITE(6.0040) THOPTC
 0040 FORMAT(1X.E12.5.5X.'THOPTC'.10X.'OPTICAL THICKNESS OF CLOUD')
       WRITE(6.0100) TSGC
 0100 FORMAT(1X.E12.5.5X.'TSGC'.12X.'CLOUD ENERGY TRANS.')
       WRITE(6.0105) TSGCW
 0105 FORMAT(1X.E12.5.5X.'TSGCW'.11X.'CLOUD-WATER ENERGY TRANS.')
       WRITE(6.0125) TSGAW
 0125 FORMAT(1X.E12.5.5X.'TSGAW'.11X.'AIR-WATER INTERFACE TRANS.')
       WRITE(6.0140) TSGW
 0140 FORMAT(1X.E12.5.5X.'TSGW'.12X.'WATER ENERGY TRANS.')
       WRITE(6.0150) FA
 0150 FORMAT(1X.E12.5.5X.'FA'.14X.'ATMOS. CONT. TO RECVD BEAM HP-ANGLE')
       WRITE(6.0152) FAW
 0152 FORMAT(1X.E12.5.5X.'FAW'.13X.'AIR-WATER CONT TO RCVD BM HP-ANGLE')
       WRITE(6.0154) FW
 0154 FORMAT(1X.E12.5.5X.'FW'.14X.'WATER CONT TO RCVD BEAM HP-ANGLE')
       WRITE(6.0158) ARDWSG
 0158 FORMAT(1X.E12.5.5X.'ARDWSG'.10X.'IN-WATER RADIANCE HP-ANGLE')
       WRITE(6.0160) FSG
 0160 FORMAT(1X.E12.5.5X.'FSG'.13X.'WATER DIST OF RADIANCE')
       WRITE(6.0170) DPWC
 0170 FORMAT(1X.E12.5.5X.'DPWC'.12X.'DELTA PULSE WIDTH-CLOUDS')
       WRITE(6.0172) DPWCW
```

5.4.3 (Continued)


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0172 FORMAT(1X,E12.5,5X,'DPWCW',11X,'DELTA PULSE WIDTH-CLOUD TO WATER')
     WRITE(6,0174) DPWW
0174 FORMAT(1X,E12.5,5X,'DPWW',12X,'DELTA PULSE WIDTH-WATER')
     WRITE(6,0180) TIPEAK
0180 FORMAT(1X,E12.5,5X,'TIPEAK',10X,'TIME OF PEAK VALUE OF PULSE')
     WRITE(6,0190) ER
0190 FORMAT(1X,E12.5,5X,'ER',14X,'TOTAL RECEIVED ENERGY PER PULSE')
     WRITE(6,0195)PRPEAK
0195 FORMAT(1X,E12.5,5X,'PRPEAK',10X,'PEAK INSTANT RECVD POWER')
     WRITE(6,0200)
0200 FORMAT(///30X,'OUTPUT FOR NOISE TECTICN'//)
     WRITE(6,0201) THOPIC
0201 FORMAT(1X,E12.5,5X,'THOPIC',10X,'OPTICAL THICKNESS OF CLOUD')
0202 WRITE(6,0203)
0203 FORMAT(/40X,'SOLAR CONTRIBUTION'/)
     IF(PRS.LT.0.0) GO TO 0298
0204 WRITE(6,0205) TSBKA
0205 FORMAT(1X,E12.5,5X,'TSBKA',11X,'CLEAR ATMOSPHERIC TRANS.')
     WRITE(6,0207) TSC
0207 FORMAT(1X,E12.5,5X,'TSC',13X,'CLCLD ENERGY TRANS.')
     WRITE(6,0209) TSKCW
0209 FORMAT(1X,E12.5,5X,'TSKCW',11X,'CLOUD TO WATER ENERGY TRANS.')
     WRITE(6,0225) TSAW
0225 FORMAT(1X,E12.5,5X,'TSAW',12X,'ENERGY TRANS,AIR-WATER INTERFACE')
     WRITE(6,0240) TSW
0240 FORMAT(1X,E12.5,5X,'TSW',13X,'WATER ENERGY TRANS.')
     WRITE(6,0250) LSR
0250 FORMAT(1X,E12.5,5X,'LSR',13X,'SPECTRAL RAD. AT RCVR APERTURE')
     WRITE(6,0260) FAS
0260 FORMAT(1X,E12.5,5X,'FAS',13X,'ATMOS. CONT TO RCVD RM HF-ANGLE')
     WRITE(6,0262) FAWS
0262 FORMAT(1X,E12.5,5X,'FAWS',12X,'AIR-WATER CONT TO RCVD RM HF ANGL')
     WRITE(6,0264) FWSO
0264 FORMAT(1X,E12.5,5X,'FWSO',12X,'WATER CONT TO RCVD RM HF-ANGLE')
     WRITE(6,0270) ARDWRS
0270 FORMAT(1X,E12.5,5X,'ARDWRS',10X,'IN-WATER RADIANCE HF-ANGLE')
     WRITE(6,0280) FRS
0280 FORMAT(1X,E12.5,5X,'FRS',13X,'FRAC INC RAD IN RCVR FLD OF VIEW')
     WRITE(6,0290) PRS
0290 FORMAT(1X,E12.5,5X,'PRS',13X,'AVERAGE BACKGROUND POWER')
     GO TO 0302
0298 WRITE(6,0299) PRS
0299 FORMAT(/1X,E12.5,5X,'PRS',13X,'***** NO SOLAR CONTRIBUTION'/)
0302 WRITE(6,0303)
0303 FORMAT(/40X,'LUNAR CONTRIBUTION'/)
     IF(PRM.LT.0.0) GO TO 0398
0304 WRITE(6,0305) TMBKA
0305 FORMAT(1X,E12.5,5X,'TMBKA',11X,'CLEAR ATMOSPHERIC TRANS.')
     WRITE(6,0307) TMC
0307 FORMAT(1X,E12.5,5X,'TMC',13X,'CLCLD ENERGY TRANS.')
     WRITE(6,0309) TMKCW
0309 FORMAT(1X,E12.5,5X,'TMKCW',11X,'CLOUD TO WATER ENERGY TRANS.')
     WRITE(6,0329) TMAW
0329 FORMAT(1X,E12.5,5X,'TMAW',12X,'ENERGY TRANS,AIR-WATER INTERFACE')
     WRITE(6,0340) TMW
0340 FORMAT(1X,E12.5,5X,'TMW',13X,'WATER ENERGY TRANS.')
     WRITE(6,0350) LMR
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5.4.3 (Continued)

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0350 FORMAT(1X,E12.5,5X,'LWR',13X,'SPECTRAL RAD. AT RCVR APERTURE')
     WRITE(6,0360) FAR
0360 FORMAT(1X,E12.5,5X,'FAR',13X,'ATPCS. CONT TO RCVD ON HF-ANGLE')
     WRITE(6,0362) FAWR
0362 FORMAT(1X,E12.5,5X,'FAWR',12X,'AIR-WATER CONT TO RCVD ON HF ANGLE')
     WRITE(6,0364) FWRC
0364 FORMAT(1X,E12.5,5X,'FWRC',12X,'WATER CONT TO RCVD ON HF-ANGLE')
     WRITE(6,0370) ARDWAR
0370 FORMAT(1X,E12.5,5X,'ARDWAR',10X,'IN-WATER RADIANCE HF-ANGLE')
     WRITE(6,0380) FRR
0380 FORMAT(1X,E12.5,5X,'FRR',13X,'FRAC INC RAD IN RCVR FLD OF VIEW')
     WRITE(6,0390) PRR
0390 FORMAT(1X,E12.5,5X,'PRR',13X,'AVERAGE BACKGROUND POWER')
     GO TO 0402
0398 WRITE(6,0399) PRR
0399 FORMAT(/1X,E12.5,5X,'PRR',13X,'***** NO LUNAR CONTRIBUTION'/)
0402 WRITE(6,0403)
0403 FORMAT(/40X,'BLUE SKY CONTRIBUTION'/)
     IF(PRBS.LE.0.0) GO TO 0450
0404 WRITE(6,0405) TOSBKA
0405 FORMAT(1X,E12.5,5X,'TOSBKA',10X,'CLEAR ATMOSPHERIC TRANS.')
     WRITE(6,0407) TOSC
0407 FORMAT(1X,E12.5,5X,'TOSC',12X,'CLOUD ENERGY TRANS.')
     WRITE(6,0409) TBKCW
0409 FORMAT(1X,E12.5,5X,'TBKCW',11X,'CLOUD TO WATER ENERGY TRANS.')
     WRITE(6,0425) TOSAW
0425 FORMAT(1X,E12.5,5X,'TOSAW',11X,'ENERGY TRANS,AIR-WATER INTERFACE')
     WRITE(6,0440) TOSW
0440 FORMAT(1X,E12.5,5X,'TOSW',12X,'WATER ENERGY TRANS.')
     WRITE(6,0450) LOSR
0450 FORMAT(1X,E12.5,5X,'LOSR',12X,'SPECTRAL RAD. AT RCVR APERTURE')
     WRITE(6,0460) FABS
0460 FORMAT(1X,E12.5,5X,'FABS',12X,'ATPCS. CONT TO RCVD ON HF-ANGLE')
     WRITE(6,0462) FAWBS
0462 FORMAT(1X,E12.5,5X,'FAWBS',11X,'AIR-WATR CONT TO RCVD ON HF-ANGLE')
     WRITE(6,0464) FWBSC
0464 FORMAT(1X,E12.5,5X,'FWBSC',11X,'WATER CONT TO RCVD ON HF-ANGLE')
     WRITE(6,0470) ARDWAB
0470 FORMAT(1X,E12.5,5X,'ARDWAB',10X,'IN-WATER RADIANCE HF-ANGLE')
     WRITE(6,0480) FRBS
0480 FORMAT(1X,E12.5,5X,'FRBS',12X,'FRAC INC RAD IN RCVR FLD OF VIEW')
     WRITE(6,0490) PRBS
0490 FORMAT(1X,E12.5,5X,'PRBS',12X,'AVERAGE BACKGROUND POWER')
     GO TO 0502
0498 WRITE(6,0499) PRBS
0499 FORMAT(/1X,E12.5,5X,'PRBS',12X,'***** NO BLUE SKY CONTRIBUTION'/)
0502 WRITE(6,0503)
0503 FORMAT(/40X,'STELLAR-ZODIACAL CONTRIBUTION'/)
     IF(PRZ.LE.0.0) GO TO 0598
0504 WRITE(6,0505) TZBKA
0505 FORMAT(1X,E12.5,5X,'TZBKA',11X,'CLEAR ATMOSPHERIC TRANS.')
     WRITE(6,0507) TZC
0507 FORMAT(1X,E12.5,5X,'TZC',13X,'CLOUD ENERGY TRANS.')
     WRITE(6,0509) TBKCW
0509 FORMAT(1X,E12.5,5X,'TBKCW',11X,'CLOUD TO WATER ENERGY TRANS.')
     WRITE(6,0525) TZAW
0525 FORMAT(1X,E12.5,5X,'TZAW',12X,'ENERGY TRANS,AIR-WATER INTERFACE')
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5.4.3 (Continued)

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      WRITE(6,0540) T2W
0540  FORMAT(1X,E12.5,5X,'T2W',13X,'WATER ENERGY TRANS.')
      WRITE(6,0550) L2R
0550  FORMAT(1X,E12.5,5X,'L2R',13X,'SPECTRAL RAD. AT RCVR APERTURE')
      WRITE(6,0560) FAZ
0560  FORMAT(1X,E12.5,5X,'FAZ',13X,'ATMOS. CONT TO RCVR ON HP-ANGLE')
      WRITE(6,0562) FAWZ
0562  FORMAT(1X,E12.5,5X,'FAWZ',12X,'AIR-WATR CONT TO RCVR ON HP-ANGLE')
      WRITE(6,0564) FWZO
0564  FORMAT(1X,E12.5,5X,'FWZO',12X,'WATER CONT TO RCVR ON HP-ANGLE')
      WRITE(6,0570) ARDWAZ
0570  FORMAT(1X,E12.5,5X,'ARDWAZ',10X,'IN-WATER RADIANCE HP-ANGLE')
      WRITE(6,0580) FMZ
0580  FORMAT(1X,E12.5,5X,'FMZ',13X,'FRAC INC RAD IN RCVR FLD OF VIEW')
      WRITE(6,0590) PBZ
0590  FORMAT(1X,E12.5,5X,'PBZ',13X,'AVERAGE BACKGROUND POWER')
      GO TO 0595
0598  WRITE(6,0599) PBZ
0599  FORMAT(/1X,E12.5,5X,'PBZ',13X,'***** NO SIEL-ZOO CONTRIBUTION'/)
0595  WRITE(6,0600)PBBL
0600  FORMAT(/40X,'BIOLUMINESCENCE'//1X,E12.5,5X,'PBBL',12X,'AVERAGE BAC
     BACKGROUND POWER')
      WRITE(6,0700)PBTOT
0700  FORMAT(//1X,E12.5,5X,'PBTOT',11X'SUM OF AVERAGE BAGRND POWER')
      WRITE(6,0800)BWE
0800  FORMAT(/,/1X,E12.5,5X,'BWE',13X,'ELECTRICAL DETECTION BANDWIDTH')
      WRITE(6,0900)
0900  FORMAT(/40X,'NOISE EQUIVALENT OPTICAL POWERS'/)
      WRITE(6,0910)NEPSB
0910  FORMAT(1X,E12.5,5X,'NEPSB',11X,'PWR-SHOT NOISE GEN. BY BKGRND')
      WRITE(6,0920)NEPTH
0920  FORMAT(1X,E12.5,5X,'NEPTH',11X,'PWR-THERMAL OR AMPLIFIER NOISE')
      WRITE(6,0930)NEPID
0930  FORMAT(1X,E12.5,5X,'NEPID',11X,'PWR-PHOTO-DETECTOR DARK CURRENT')
      WRITE(6,0940)NEPSS
0940  FORMAT(1X,E12.5,5X,'NEPSS',11X,'PWR-SHOT NOISE GEN. BY SIGNAL')
      WRITE(6,0950)NEPTOT
0950  FORMAT(1X,E12.5,5X,'NEPTOT',10X,'NOISE EQ. POWER-ALL SOURCES')
      GO TO 9999
C     ERROR MESSAGES
9000  WRITE(6,9001)
9001  FORMAT(1X,'ERROR.  THOPIC IS NEGATIVE')
      GO TO 9999
9005  WRITE(6,9006)
9006  FORMAT(1X,'ERROR. V IS NOT WITHIN LIMITS FOR LOOKUP TABLE')
      GO TO 9999
9010  WRITE(6,9011)
9011  FORMAT(1X,'ERROR. ZASGA IS NOT WITHIN LIMITS FOR LOOKUP TABLE')
      GO TO 9999
9015  WRITE(6,9016)
9016  FORMAT(1X,'ERROR. ARDWGS IS NOT WITHIN LIMITS FOR LOOKUP TABLE')
      GO TO 9999
9020  WRITE(6,9021)
9021  FORMAT(1X,'ERROR. ARDWGN SOLAR ACT IN LIMITS FOR LOOKUP TABLE')
      GO TO 9999
9025  WRITE(6,9026)
9026  FORMAT(1X,'ERROR. ARCWGN LUNAR ACT IN LIMITS FOR LOOKUP TABLE')
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5.4.3 (Continued)

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      GO TO 9999
 9030 WRITE(6,9031)
 9031 FORMAT(1X,'ERROR. ARGSCN BSAV NOT IN LIMITS FOR LOOKUP TABLE')
      GO TO 9999
 9035 WRITE(6,9036)
 9036 FORMAT(1X,'ERROR. ARGNUM STZLO NOT IN LIMITS FOR LOOKUP TABLE')
      GO TO 9999
 9040 WRITE(6,9041)
 9041 FORMAT(1X,'ERROR. THOPTA NOT IN LIMITS FOR LOOKUP TABLE.')
 9999 RETURN
      END
 3000 REAL FUNCTION INTERP(X)
      IMPLICIT REAL(A-Z)
      INTEGER I,J,NPR,NTP
C     LINEAR INTERPOLATION TO DETERMINE WATER DISTRIBUTION OF RADIANCE
C
      DIMENSION PHIMF(20),PHI(20)
      DATA PHIMF/0.0,3.8,7.6,11.4,15.2,19.0,22.8,26.5,30.2,33.9,
     $37.5,41.1,44.6,48.1,51.6,54.9,58.2/,PHI0/0.0,5.0,10.0,15.0,
     $20.0,25.0,30.0,35.0,40.0,45.0,50.0,55.0,60.0,65.0,70.0,
     $75.0,80.0,85.0,90.0/
C
C     FIND ANGULAR INTERVAL
      I=0
 3010 I=I+1
      IF(X-PHIMF(I)) 3020,3100,3010
C     INTERPOLATION FOLLOWS
 3020 INTERP=(X-PHIMF(I-1))/(PHIMF(I)-PHIMF(I-1))*5.+PHI0(I-1)
      RETURN
C     NO INTERPOLATION NECESSARY
 3100 INTERP=PHI0(I)
      RETURN
      END
C
C
 5000 REAL FUNCTION UNLIN(V,ZAS)
      IMPLICIT REAL(A-Z)
      INTEGER I,J,NPR,NTP
      DIMENSION TABLE(120,10)
C     ROUTINE SPEED (V) IN METERS/SECOND
      DATA TABLE/-5.,0.,5.,10.,15.,20.,25.,30.,35.,40.,45.,
     $50.,55.,60.,65.,70.,75.,80.,85.,90.,0.0,.979,.975,
     $.964,.945,.920,.887,.841,.860,.747,.687,.620,.940,
     $.469,.305,.295,.203,.113,.0341,.C.1.03,.977,.974,
     $.982,.944,.910,.805,.845,.790,.745,.685,.619,.946,
     $.468,.305,.290,.209,.126,.0610,.C205,2.04,.976,.972,
     $.981,.947,.917,.804,.899,.797,.702,.689,.617,.949,
     $.468,.305,.299,.214,.130,.0351,.C390,4.12,.974,.970,
     $.959,.940,.914,.801,.841,.794,.741,.681,.615,.943,
     $.466,.300,.303,.224,.151,.0945,.C594,7.21,.970,.966,
     $.955,.936,.910,.877,.837,.790,.736,.677,.611,.540,.465,
     $.387,.310,.236,.172,.119,.0809,1C.3,.967,.963,.951,.933,.907,.873,
     $.833,.780,.733,.673,.608,.538,.464,.389,.315,.247,.180,.139,.0901,
     $13.4,.963,.959,.940,.925,.901,.870,.829,.782,.729,.669,.605,.536,
     $.464,.391,.321,.255,.197,.148,.1C0,16.5,.960,.956,.944,.920,.899,
     $.866,.826,.779,.725,.666,.602,.534,.464,.393,.325,.262,.206,.157,
     $.117,19.6,.956,.952,.941,.922,.896,.863,.822,.775,.722,.663,.599,
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5.4.3 (Continued)


```
     1.532,.463,.395,.325,.260,.213,.165,.126/
C     FUNCTION WILL INTERPOLATE TO FIND TIME-AVERAGED UPWELLING AIR-SEA
C     INTERFACE TRANSMITTANCE FOR THOPIC.GT.0 AND THOPIC.LT.10
C
C     FIND WIND SPEED INTERVAL
      J=0
 5010 J=J+1
C
      IF(V-TABLE(1,J)) 5020,5020,5010
C     FIND SIGNAL ZENITH ANGLE INTERVAL
 5020 I=0
 5030 I=I+1
      IF(ZAS-TABLE(I,1)) 5044,5040,5030
C
C     FOLLOWING CHECKS TO SEE WHAT TYPE OF INTERPOLATION IS NECESSARY
C
 5040 IF(V.EQ.TABLE(1,J).AND.ZAS.EQ.TABLE(I,1)) GO TO 5060
 5042 IF(V.NE.TABLE(1,J).AND.ZAS.EQ.TABLE(I,1)) GO TO 5070
 5044 IF(V.EQ.TABLE(1,J).AND.ZAS.NE.TABLE(I,1)) GO TO 5080
C
C     INTERPOLATION FOLLOWS
C
 5050 CHE INK=((TABLE(I,1)-ZAS)*((TABLE(I,J)-V)*TABLE(I-1,J-1)+
     2(TABLE(1,J)-ZAS)*(V-TABLE(1,J-1))*TABLE(I-1,J)+
     3(ZAS-TABLE(I-1,1))*((TABLE(1,J)-V)*TABLE(I,J-1)+
     4(ZAS-TABLE(I-1,1))*(V-TABLE(1,J-1))*TABLE(I,J))/
     5(TABLE(1,J)-TABLE(1,J-1))/((TABLE(I,1)-TABLE(I-1,1))
C
C     INTERPOLATION FOR BOTH PARAMETERS
C
      RETURN
C
 5060 CHE INK=TABLE(I,J)
C
C     NO INTERPOLATION NECESSARY
      RETURN
 5070 CHE INK=TABLE(I,J-1)-((V-TABLE(1,J-1))/(TABLE(1,J)-TABLE(1,
     $J-1))*(TABLE(I,J-1)-TABLE(I,J)))
C
C     INTERPOLATION FOR WIND SPEED ONLY
      RETURN
C
 5080 CHE INK=TABLE(I-1,J)-((ZAS-TABLE(I-1,1))/(TABLE(I,1)-
     $TABLE(I-1,1))*(TABLE(I-1,J)-TABLE(I,J)))
C
C     INTERPOLATION FOR ZENITH ANGLE ONLY
      RETURN
      END
C
 6000 REAL FUNCTION E2(B)
      IMPLICIT REAL(A-Z)
      INTEGER I,J,NPM,NTP
C     FUNCTION TO EVALUATE EXPONENTIAL INTEGRAL WHERE B IS EFFECTIVE
C     CLEAR ATMOSPHERE OPTICAL THICKNESS
C
      DIMENSION TABLE2 (21,2)
      DATA TABLE2/.2,.22,.24,.26,.28,.30,.32,.34,.36,.38,.40,
```

5.4.3 (Continued)

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TSO03.USPLPR.FORT
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```
     1.47,.44,.46,.48,.50,.52,.54,.56,.58,.60,.5742,.5505,              00009700
     1.5283,.5075,.4878,.4691,.4515,.4348,.4189,.4037,.3894,            00009710
     1.3756,.3626,.3500,.3381,.3264,.3157,.3052,.2951,.2855,            00009720
     1.2762/                                                            00009730
C                                                                       00009740
C     FIND INTERVAL FOR B                                               00009750
      I=0                                                               00009760
 6010 I=I+1                                                             00009770
      IF(B-TABLE2(I,1)) 6020,6100,6010                                  00009780
C     INTERPOLATION FOLLOWS                                             00009790
 6020 F2=TABLE2(I-1,2)-(B-TABLE2(I-1,1))/0.02)*(TABLE2(I-1,2)-TABLE2(I,00009800
     12))                                                               00009810
      RETURN                                                            00009820
C     NO INTERPOLATION NECESSARY                                        00009830
 6100 F2=TABLE2(I,2)                                                    00009840
      RETURN                                                            00009850
      END                                                               00009860
 7000 REAL FUNCTION WTRANS(SUM,ARFOV,NDEX)                              00009870
      IMPLICIT REAL(A-Z)                                                00009880
      PI=2.*ARCOS(0.0)                                                  00009890
      COFOV=COS(ARFOV*PI/180.)                                          00009900
      VAR=SUM/COFOV                                                     00009910
C     FIND VALUES OF INTEGRAL E1 FROM LOOKUP TABLE                       00009920
      TERM1=E1(SUM)                                                     00009930
      TERM2=E1(VAR)                                                     00009940
C     CALCULATE WATER TRANSMISSION COEFFICIENT FOR A DISPERSED          00009950
C     LIGHT SOURCE                                                      00009960
      WTRANS=NDEX**2.*(SUM**2.*(TERM1-TERM2)+(1.-SUM)*EXP(-1.*SUM)-(1.-V00009970
     1AR)*EXP(-1.*VAR)*COFOV**2.)                                       00009980
      RETURN                                                            00009990
      END                                                               00010000
 7500 REAL FUNCTION E1(B)                                               00010010
      IMPLICIT REAL(A-Z)                                                00010020
      INTEGER I,J,NPM,NIP                                               00010030
C     FUNCTION TO EVALUATE EXPONENTIAL INTEGRAL                         00010040
C                                                                       00010050
      DIMENSION TABLE3(88,2)                                            00010060
      DATA TABLE3/2.0,2.1,2.2,2.3,2.4,2.5,2.6,2.7,2.8,2.9,3.0,3.1,3.2,  00010070
     13.3,3.4,3.5,3.6,3.7,3.8,3.9,4.0,4.1,4.2,4.3,4.4,4.5,4.6,4.7,4.8,  00010080
     14.9,5.0,5.1,5.2,5.3,5.4,5.5,5.6,5.7,5.8,5.9,6.0,6.1,6.2,6.3,6.4,  00010090
     16.5,6.6,6.7,6.8,6.9,7.0,7.1,7.2,7.3,7.4,7.5,7.6,7.7,7.8,7.9,8.0,  00010100
     18.1,8.2,8.3,8.4,8.5,8.6,8.7,8.8,8.9,9.0,9.1,9.2,9.3,9.4,9.5,9.6,  00010110
     19.7,9.8,9.9,10.,11.,11.,12.50,14.25,15.30,16.07,18.10,20.,.4890E-01,00010120
     1.4261E-01,.3719E-01,.3250E-01,.2844E-01,.2491E-01,.2185E-01,.1918 00010130
     1E-01,.1686E-01,.1482E-01,.1305E-01,.1149E-01,.1013E-01,.8939E-02, 00010140
     1.7891E-02,.6970E-02,.6160E-02,.5448E-02,.4820E-02,.4267E-02,.3779 00010150
     1E-02,.3349E-02,.2969E-02,.2633E-02,.2336E-02,.2073E-02,.1841E-02, 00010160
     1.1635E-02,.1453E-02,.1292E-02,.1148E-02,.1021E-02,.9086E-03,      00010170
     1.8086E-03,.7198E-03,.6409E-03,.5708E-03,.5084E-03,.4532E-03,      00010180
     1.4039E-03,.3601E-03,.3211E-03,.2864E-03,.2555E-03,.2280E-03,      00010190
     1.2034E-03,.1816E-03,.1621E-03,.1448E-03,.1293E-03,.1155E-03,      00010200
     1.1032E-03,.9219E-04,.8239E-04,.7364E-04,.6583E-04,.5886E-04,      00010210
     1.5263E-04,.4707E-04,.4211E-04,.3770E-04,.3370E-04,.3016E-04,      00010220
     1.2699E-04,.2415E-04,.2162E-04,.1936E-04,.1733E-04,.1552E-04,      00010230
     1.1390E-04,.1245E-04,.1115E-04,.9988E-05,.8949E-05,.8018E-05,      00010240
     1.7185E-05,.6439E-05,.5771E-05,.5173E-05,.4637E-05,.4157E-05,      00010250
     1.1247E-07,.2770E-08,.4C5?E-09,.1280-09,.3278-10,.6656-11,.9056-12/ 00010260
```

5.4.3 (Continued)

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TSOBJ.DSPDPH.FORT
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```
C
C      FIND INTERVAL FOR B
       I=0
 7510  I=I+1
       IF(B-TABLE3(I,1)) 7520,7600,7510
C      INTERPOLATION FOLLOWS
 7520  E1=TABLE3(I-1,2)-((B-TABLE3(I-1,1))/(TABLE3(I,1)-TABLE3(I-1,1)))*
      $TABLE3(I-1,2)-TABLE3(I,2))
       RETURN
C      NO INTERPOLATION NECESSARY
 7600  E1=TABLE3(I,2)
       RETURN
       END
```

5.4.3 (Continued)

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ISOBJ.SORT.FORT
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```
      SUBROUTINE SORT(ARRAY1,ARRAY2,N)                              00000010
      INTEGER I,J,N,NLOOP                                           00000020
      LOGICAL DONE                                                  00000030
      DIMENSION ARRAY1(N),ARRAY2(N)                                 00000040
      DO 100 I=2,N                                                  00000050
      DONE=.TRUE.                                                   00000060
C     DONE IS FLAG TO DETERMINE IF ALL SORTING IS COMPLETE          00000070
      NLOOP=N-I+1                                                   00000080
C     NLOOP IS WHERE ACTUAL EXCHANGES TAKE PLACE                    00000090
C     ARRAY1 IS SORTED.  ARRAY2 ELEMENTS ARE MOVED ONLY WHEN        00000095
C     CORRESPONDING ELEMENTS IN ARRAY1 ARE MOVED.                   00000096
C                                                                   00000097
      DO 90 J=1,NLOOP                                               00000100
      IF(ARRAY1(J).GE.ARRAY1(J+1)) GO TO 90                         00000110
      TEMP1=ARRAY1(J+1)                                             00000120
      TEMP2=ARRAY2(J+1)                                             00000125
      ARRAY1(J+1)=ARRAY1(J)                                         00000130
      ARRAY2(J+1)=ARRAY2(J)                                         00000135
      ARRAY1(J)=TEMP1                                               00000140
      ARRAY2(J)=TEMP2                                               00000145
      DONE=.FALSE.                                                  00000150
   90 CONTINUE                                                      00000160
  100 IF(DONE) RETURN                                               00000170
C     EXIT POINT FROM SUBROUTINE                                    00000180
      RETURN                                                        00000190
      END                                                           00000200
```

5.4.3 (Continued)

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TSOBJ.DSTRD2.FORT
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```
      REAL FUNCTION DSTRD2 (ADLTA,ANDW,ARFOV)
C     THE FOLLOWING WILL CALCULATE THE DISTRIBUTION OF RADIANCE DUE TO
C     SIGNAL OR A NOISE SOURCE.  TABLES ARE DEVELOPED IN TERMS OF ARFOV,
C     THE HALF-ANGLE OF RECEIVER FIELD OF VIEW.  LAYER1 REFERS TO ARFOV-
C     15,LAYER2 REFERS TO ARFOV-20,LAYER3 REFERS TO ARFOV-25. LAYER4
C     REFERS TO ARFOV-30.
C
C
      IMPLICIT REAL (A-Z)
      INTEGER I,J,K
C
      DIMENSION IDLTA(19),IPHIO(13),TABLE(13,19),LAYER1(13,19),
     &LAYER2(13,19),LAYER3(13,19),LAYER4(13,19),DSTRAD(13,19,4)
      EQUIVALENCE (LAYER1(1,1),DSTRAD(1,1,1)),(LAYER2(1,1),DSTRAD(1,1,2
     &)),(LAYER3(1,1),DSTRAD(1,1,3)),(LAYER4(1,1),DSTRAD(1,1,4))
C
      DATA IDLTA/0.,5.,10.,15.,20.,25.,30.,35.,40.,45.,50.,55.,60.,65.,
     &70.,75.,80.,85.,90./,IPHIO/15.,20.,25.,30.,35.,40.,45.,50.,55.,
     &60.,65.,70.,75./
C
C
      DATA LAYER1/.9999,.7906,.5974,.5015,.4,.33,.2600,.2,.1599,
     &.13,.1,.1,.1,.9061,.7458,.5693,.5367,.3622,.2712,.2305,
     &.1912,.1614,.1516,.1318,.1143,.1112,.6020,.5711,.4706,.3893,.3169,
     &.2962,.2156,.1066,.1603,.1372,.1263,.1125,.1073,.4163,.3072,.3521,
     &.3164,.2761,.2300,.1966,.1793,.1522,.1310,.1233,.1072,.1031,.1058,
     &.2193,.2305,.2292,.2207,.1960,.1758,.1515,.1406,.1203,.1144,.1007,
     &.0902,.0613,.3050,.1266,.1471,.1544,.1533,.1476,.1374,.1255,.1061,
     &.1033,.0976,.0881,.0,.0203,.0509,.0766,.0913,.1042,.1136,.1052,
     &.1001,.0995,.0874,.0845,.0833,20.0,.0102,.0311,.0462,.0648,.0776,
     &.0062,.0815,.0794,.0733,.0773,.0717,30.0,.0053,.0203,.0351,.0468,
     &.0555,.0652,.0695,.0637,.0666,.0639,40.0,.0035,.0133,.0238,.0354,
     &.0424,.0454,.0528,.0529,.0517,50.0,.0034,.0080,.0165,.0266,.0354,
     &.0305,.0390,.0427,60.0,.0022,.0073,.0138,.0211,.0262,.0290,.0327,
     &70.0,.0007,.0056,.0099,.0152,.0185,.0219,80.0,.0007,.0027,.0060,
     &.0102,.0150,90.0,.0006,.0025,.0054,.0091,100.0,.0005,.0022,.0040,
     &110.0,.0005,.0019,120.0,.0004,130.0/
C
C
      DATA LAYER2/.9999,.9999,.8753,.7039,.6094,.5132,.4184,.3273,.28,
     &.24,.22,.2,.18,.9999,.9417,.8237,.6812,.5566,.4557,.3755,
     &.3250,.2804,.2466,.2207,.1942,.1899,.9229,.8118,.6980,.5985,.5077,
     &.4236,.3602,.3133,.2706,.2382,.2168,.1904,.1860,.7118,.6254,.5441,
     &.4937,.4337,.3827,.3308,.2918,.2534,.2285,.2084,.1816,.1751,.4364,
     &.4165,.3926,.3744,.3485,.3189,.2865,.2629,.2327,.2159,.1909,.1775,
     &.1899,.1921,.2347,.2578,.2611,.2638,.2553,.2429,.2227,.2072,.1934,
     &.1766,.1634,.1565,.0625,.0958,.1397,.1626,.1800,.1869,.1905,.1867,
     &.1767,.1602,.1570,.1509,.1409,.0,.0208,.0574,.0830,.1098,.1251,
     &.1380,.1392,.1443,.1404,.1334,.1290,.1272,20.0,.0107,.0351,.0570,
     &.0727,.0804,.1006,.1009,.1124,.1112,.1098,.1064,30.0,.0053,.0215,
     &.0411,.0504,.0672,.0785,.0861,.0925,.0937,.0927,40.0,.0040,.0159,
     &.0290,.0432,.0527,.0593,.0650,.0711,.0749,50.0,.0034,.0108,.0195,
     &.0296,.0603,.0468,.0515,.0586,60.0,.0022,.0077,.0157,.0263,.0318,
     &.0362,.0437,70.0,.0011,.0057,.0130,.0177,.0225,.0278,80.0,.0007,
     &.0039,.0085,.0142,.0169,90.0,.0006,.0025,.0057,.0100,100.0,.0005,
     &.0022,.0350,110.0,.0005,.0019,120.0,.0004/
C
```

5.4.3 (Continued)

```
                                                          FSORJ.DSIRD2.FORT                PAGE 0002
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C                                                                          00000580
      DATA LAYER3/.9999,.9994,1.,.92,.0208,.65,.59,.58,.42,                00000590
     $.37,.33,.29,.26,.9999,.9994,.9641,.8731,.7610,.6400,.5512,           00000600
     $.6205,.6155,.5561,.5521,.2925,.2819,.9999,.9561,.8715,.7853,.6875,   00000610
     $.6040,.5186,.4536,.3970,.3575,.3237,.2870,.2762,.9301,.8337,.7367,   00000620
     $.6610,.5959,.5361,.4899,.4222,.3716,.3547,.3075,.2795,.2625,.7203,   00000630
     $.6619,.5836,.5341,.4919,.4510,.4174,.3806,.3439,.3148,.2858,.2629,   00000640
     $.2518,.4927,.4366,.4200,.4018,.3862,.3696,.3504,.3251,.3110,.2821,   00000650
     $.2634,.2622,.2363,.2050,.2432,.2714,.2758,.2838,.2877,.2786,.2706,   00000660
     $.2627,.2301,.2313,.2217,.2156,.0510,.0715,.1558,.1753,.1910,.2031,   00000670
     $.2032,.2113,.2073,.2036,.2028,.1919,.1888,.0,.0238,.0597,.0893,      00000680
     $.1179,.1358,.1520,.1600,.1692,.1697,.1705,.1705,.1646,20.0,          00000690
     $.0125,.0358,.0603,.0808,.0990,.1112,.1210,.1338,.1319,.1392,         00000700
     $.1357,30.0,.0051,.0219,.0431,.0623,.0730,.0898,.1006,.1078,          00000710
     $.1136,.1158,40.0,.0051,.0187,.0330,.0462,.0575,.0663,.0782,          00000720
     $.0811,.0887,29.0,.0038,.0111,.0192,.0327,.0422,.0562,.0609,          00000730
     $.0688,60.0,.0027,.0091,.0186,.0257,.0362,.0419,.0480,70.0,           00000740
     $.0011,.0373,.0158,.0188,.0257,.0319,80.0,.0010,.0019,.0087,          00000750
     $.0151,.0205,90.0,.0009,.0016,.0079,.0119,100.0,.0005,.0024,.0056,    00000760
     $110.0,.0305,.0021/                                                   00000770
C                                                                          00000780
C                                                                          00000790
      DATA LAYER4/.9999,.9999,1.,1.,.9417,.0057,.7217,.6321,.56,.5,        00000800
     $.44,.40,.37,.9999,.9999,1.,.9797,.9005,.8060,.7092,.6247,            00000810
     $.5505,.4942,.4501,.4016,.3839,.9999,.9999,.9713,.9077,.8391,.7623,   00000820
     $.6766,.5967,.5363,.4804,.4402,.4323,.3760,.9999,.9625,.8888,.8180,   00000830
     $.7405,.6807,.6128,.5667,.4996,.4571,.4201,.3834,.3610,.9373,.8449,   00000840
     $.7721,.6921,.6303,.5873,.5406,.5056,.4603,.4261,.3931,.3677,.3421,   00000850
     $.7346,.6594,.5991,.5561,.5211,.4910,.4637,.4408,.4076,.3842,.3581,   00000860
     $.3317,.3175,.4626,.4479,.4360,.4204,.4087,.3916,.3815,.3647,.3525,   00000870
     $.3390,.3266,.3021,.2943,.2086,.2565,.2827,.2922,.3026,.3039,.3013,   00000880
     $.2903,.2965,.2889,.2807,.2658,.2581,.0430,.1052,.1559,.1835,.2071,   00000890
     $.2204,.2306,.2335,.2381,.2339,.2348,.2120,.2285,.0,.0220,.0609,      00000900
     $.0957,.1290,.1499,.1661,.1757,.1871,.1905,.1933,.1960,.1960,20.0,    00000910
     $.0125,.0610,.0633,.0866,.1067,.1299,.1361,.1472,.1525,.1586,.1620,   00000920
     $30.0,.0057,.0240,.0446,.0641,.0806,.0964,.1087,.1152,.1219,.1290,    00000930
     $40.0,.0053,.0191,.0330,.0521,.0654,.0735,.0848,.0756,.0979,50.0,     00000940
     $.0038,.0111,.0246,.0367,.0485,.0616,.0652,.0755,60.0,.0022,.0091,    00000950
     $.0190,.0293,.0384,.0451,.0551,70.0,.0011,.0084,.0157,.0223,.0275,    00000960
     $.0358,80.0,.0013,.0119,.0096,.0154,.0215,90.0,.0009,.0016,.0379,     00000970
     $.0138,100.0,.0008,.0032,.0058/                                       00000980
      I=0                                                                  00000990
      J=0                                                                  00001000
      DSIRD2=-100.                                                         00001010
      ANGLE=10.                                                            00001020
C     INITIALIZE ARRAY DIMENSIONS AND VALUE OF ANGLE FOR LOOP 10           00001030
C     INITIALIZE VALUE TO BE RETURNED                                      00001040
      IFLAG=0.0                                                            00001050
      JFLAG=0.0                                                            00001060
      ZFLAG=0.0                                                            00001070
C     INITIALIZE FLAGS FOR ERROR NOTIFICATION.                             00001080
C                                                                          00001100
    2 IF(ADELTA.LT.0.0.OR.ADELTA.GT.90.0)IFLAG=1.0                         00001110
    4 IF(AROW.LT.15.0.OR.AROW.GT.75.0)IFLAG=1.0                            00001120
    6 IF(ARFOV.NE.15.0.AND.ARFOV.NE.20.0.AND.ARFOV.NE.25.0.AND.            00001130
     $ARFOV.NE.30.0)JFLAG=1.0                                              00001140
    8 IF(IFLAG.EQ.1.0.OR.JFLAG.EQ.1.0.OR.ZFLAG.EQ.1.0)GO TO 9998           00001150
```

5.4.3. (Continued)

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```
C     CHECK TO SEE IF PARAMETERS ARE WITHIN RANGES SPECIFIED
C
C
   10 J=J+1
      IF(ADELTA-DELTA(J))20,20,10
C     FIND NECESSARY RANGE FOR INTERPOLATION OF ADELTA
C
   20 I=I+1
C     CALCULATE VALUE OF NUMERATOR FOR INTERPOLATION
      IF(ARDW-IPHIO(I))30,30,20
C     FIND SMALLEST IPHIO .GE. ARDW FOR CALCULATION
C
   30 DO 90 I=1,6
      ANGLE=ANGLE+5.
      IF(ARDW.EQ.ANGLE)GO TO 1500
C     DETERMINE VALUE OF ARDW
   90 CONTINUE
C
C
 1000 NUM=5.-(DELTA(J)-ADELTA)
      IF (NUM.EQ.5.0)GO TO 2000
C
 1500 DSTRD2=NUM/5.*(DSTRAD(I,J,Z)-DSTRAD(I,J-1,Z))+DSTRAD(I,J-1,Z)
C     THIS STATEMENT PERFORMS ACTUAL INTERPOLATION
C
      RETURN
C
C
 2000 DSTRD2=DSTRAD(I,J,Z)
C     NO INTERPOLATION IS NECESSARY.
      RETURN
C
C
 9998 WRITE(6,9999)
 9999 FORMAT(1X,'THERE IS AN ERROR IN PARAMETERS.  DSTRD2 RETURNS DEFAUL
     *T VALUE OF -100.0')
99999 RETURN
      END
```

5.5 MODEL UNCERTAINTIES

The sub-models developed in Section 5.3 have very few uncertainties, and should require little future revision.

5.5.1 Area Relationships

The only uncertainty here involves the size and shape of environmental resolution elements (ERE's). The ERE concept itself is too useful to be neglected, but future cloud and water data base work may reveal that ERE's of a different size or shape are more appropriate in the OSCAR applications.

5.5.2 Temporal Relationships

There are no uncertainties in the models for the temporal relationships in Section 5.3.2.

5.5.3 Message

There are no uncertainties in the models for the message in Section 5.3.3.

5.5.4 Modulation/Demodulation

The only uncertainties in the models developed in Section 5.3.4 concern their completeness. There may be other demodulation and message processing approaches which will change the required Signal-to-Noise ratio and/or Message Lengths (Overhead bits) from the present formulation. GTE-Sylvania will continue to search for these improved demodulation techniques in related work.

A second-order uncertainty concerns our model for jamming/spoofing, and the five assumptions made there-in. If those assumptions were altered by the NAVY, the related sub-models would also require modification.

5.5.5 Scanning Relationships

There is no uncertainty in the model developed in Section 5.3.5. However, as the hardware design progresses, the formulation of the satellite pointing accuracy may be changed to better reflect the attitude stabilization and pointing technique actually employed. This will probably be a minor analytic change.

5.5.6 Receiver and Source

There are no uncertainties in the models developed in Section 5.3.6.

5.5.7 Availability/System Effectiveness and Adaptive Scanning

The sub-models for adaptive scanning may be modified as more is learned about:

1. The precision of the information obtainable from remote scanning;

2. The practicality of the angular expansion/elliptical correction optics.

It may happen that only relatively crude information is available concerning the clouds in the coverage area, and that a continuously variable beam size is not practical, so that some straightforward model modification should occur.

5.5.8 Included SPDPM Sub-Models

The propagation related SPDPM sub-models were discussed in Sections 3.4 and 4.5. The SPDPM system design sub-models are well understood. The only one requring possible modification is the pulse-shape/detection bandwidth, if the atomic resonance optical filter becomes the leading candidate, since this filter adds an additional pulse stretching/distortion to that caused by the propagation path/field-of-view effects.

Table 5-3 summarizes the status of the DCM sub-models.

5.5.8 (Continued)

TABLE 5-3. STATUS OF SUB-MODELS OF THE DCM
(SPDPM models are discussed in Sections 3.4 and 4.5)

SUB-MODEL	STATUS	COMMENT
Area Relationship	O.K. in principle	Size and shape of environmental resolution elements may be modified in future.
Temporal Relationships	O.K.	-
Message	O.K.	-
Modulation/Demodulation	O.K. as written	Further work on better schemes continues, and may modify these models. Changing the "threat" assumptions would change the spoofing/jamming models.
Scanning Relationships	O.K. as written	Satellite design work may redefine the pointing accuracy sub-model.
Receiver and Source	O.K.	-
Availability/Adaptive Scanning	O.K. as written	Probably will be modified as the remote sensing precision and practical optical designs are better understood.
SPDPM - Environmental	Partially Verified	See discussion in Sections 3.4 and 4.5
SPDPM - System Design	O.K. as written	Will require modification if atomic resonance filter becomes the leading candidate.

5.6 "PARAMETER VALUE" UNCERTAINTIES

The parameter value uncertainties for the DCM are of quite a different type than those for the SPDPM. Here the uncertainties primarily relate to those hardware parameters which are actually achievable.

5.6.1 Environment

Those environmental inputs unique to the DCM include:

A_{RE} = area of a single environmental resolution element. This is uncertain and will remain so until sufficient cloud and water data base development occurs to uniquely define it.

R_{SU} = distance from sun to receiver. This is well known to the required accuracy.

λ_{SU} = solar latitude is also well known to the required accuracy.

β_{SU} = solar longitude is also well known to the required accuracy.

R_E = mean earth radius is well known.

R_{MU} = distance from moon to receiver. This is well known to the required accuracy.

λ_{MU} = lunar latitude is well known to the required accuracy.

β_{MU} = lunar longitude is also well known to the required accuracy.

The environmental SPDPM inputs were discussed in Sections 3.5 and 4.6 from the point-of-view of the values existing along a single propagation path. Use of the SPDPM in the DCM requires the additional information of their simultaneous values throughout a satellite coverage area. The cloud properties are particularly uncertain when such correlated information is desirable, and the water properties are only approximately known over large stretches of the coverage area.

Better data base development must occur in order to provide adequate inputs to the DCM.

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5.6.2 Requirements

There is no uncertainty in any of the requirements inputs listed in Section 5.2.2.

5.6.3 System Design

Considering the present state-of-the-art in laser and filter technology, it is not surprising that there are significant uncertainties in many aspects of the system design inputs. These inputs and their uncertainties include:

$t_{s\ell}$ = slew time, scan time or dead time between illuminated spots. The value of this parameter depends on the details of the transmitter optics design and the scan technique used, both of which remain to be determined.

t_W = source warm-up time. Since the laser source is unknown, so is a precise value for this parameter.

PRF = source repetition frequency. This parameter depends on the most efficient laser operating point, the choice of ℓ, the minimum slot width achievable and the number of lasers aboard the space-craft, all of which are not precisely determined at this time.

G_{EL} = Off-zenith in-water receiver pointing angle. The optimum value of this parameter will remain uncertain until water propagation experiments and water data base development work is accomplished.

G_{AZ} = Azimuth receiver pointing angle. The same comments apply as for G_{EL}.

m = Number of simultaneously active lasers aboard the satellite. This is unknown until a particular laser candidate is selected, and its optimal operating point is determined.

E_p = Energy per pulse of each active laser aboard the satellite. The same comments apply as for m.

F_L = Wall plug laser efficiency. Same comments as for m.

P'_{HO} = prime power on the satellite required for all non-laser functions. This parameter depends on future satellite design.

5.6.3 (Continued)

R_S = satellite altitude. This will be sufficiently known for all candidate orbits.

α_S = Satellite latitude. This will be sufficiently known for all candidate orbits.

θ_S = Satellite longitude. This will be sufficiently known for all candidate orbits.

t_f = dead time between frames. This again depends on the details of the laser, and its minimum time-to-refire.

t_s = slot width. This depends on the pulse stretching encountered in the environment, and so will remain uncertain until extensive clould propagation experiments and cloud data base development occurs.

ℓ = number of bits per pulse. This parameter depends on slot width and minimum achievable spot size, both of which remain to be determined.

ϵ = overlap factor between illuminated spots. This is not uncertain so long as a random spot scan is employed.

θ_{TS} = Satellite short term angular jitter. This parameter is unknown until further design is accomplished.

θ_{TDR} = Satellite long term angular drift. Same comment as for θ_{TS}.

The system design inputs for the SPDPM were not discussed previously, since Section 3.5 and 4.6 emphasized the environmental parameters. The primary uncertainty, beyond those discussed above, lies in the receiver; in particular:

θ_R = Receiver half angle field-of-view. This will not be known until adequate water propagation experiments and water data base development occur

γ_R = Receiver (primarily filter) transmission. This will not be known until the filter type and receiver field-of-view are known.

5.6.3 (Continued)

B_{OPT} = filter bandpass. This will not be known until the filter type and receiver field-of-view are known.

Table 5-4 summarizes the status of the input parameters of the DCM.

5.6.3 (Continued)

Table 5-4. Status of "Input Parameters" to DCM

PARAMETER	STATUS	COMMENT
ENVIRONMENT	PARTIAL	cf SPDPM discussion in Section 3.5 and 4.6. Distribution/Correlation of environmental parameters is unknown.
REQUIREMENTS	O.K.	——
SYSTEM DESIGN		
$t_{s\ell}$	TBD	Depends on system design details.
t_w	TBD	Depends on laser selected.
PRF	TBD	Depends on laser and slotwidth.
G_{EL}, G_{AZ}	TBD	Depends on water propagation experiment
m	TBD	Depends on laser characteristics
E_p	TBD	Depends on laser characteristics
F_L	TBD	Depends on laser characteristics
P'_{HO}	TBD	Depends on details of satellite design
R_S, α_S, β_S	O.K.	Known for each candidate orbit.
t_f	TBD	Depends on laser characteristics.
t_s	TBD	Depends on extensive cloud propagation results.
ℓ	TBD	Depends on slot width and spot size.
ϵ	O.K.	Known so long as random scan is used.
$\theta_{TS}, \theta_{TDR}$	Partially known	Depends on details of satellite design.
θ_R	TBD	Depends on water propagation experiment.
γ_R	TBD	Depends on filter characteristics.
B_{OPT}	TBD	Depends on filter characteristics.

Section 6

FULL OSCAR SYSTEM MODEL

This section discusses the model for the full OSCAR system, including the ground stations, microwave uplink, satellite orbits, optical downlink and submarine terminal. The section is organized as follows:

6.1 Full OSCAR Systems Model -- Philosophy and Flow Charts

6.1.1 Philosophy of Approach -- Full OSCAR System Model

6.1.2 Model Flow Chart -- Full OSCAR Model

6.2 Input Information

6.2.1 Environment

6.2.1.1 Fixed Data Bases

6.2.1.2 Data Bases with Predictable Variations

6.2.1.3 Data Bases with Unpredictable Variations

6.2.2 Requirements

6.2.3 System Design

6.2.3.1 Ground Station

6.2.3.2 Satellites

6.2.3.3 Submarine Terminals

6.3 Environment, Requirements, System Design Considerations

6.3.1 Environment

6.3.1.1 Data Bases with Predictable Variation

6.3.1.1.1 Solar Location

6.3.1.1.2 Lunar Location/Brightness

6.3.1.1.3 Ice Location

6.3.2 Requirements

6.3.2.1 System Effectiveness

6.3.2.1.1 Basic Definitions

6.3.2.1.2 Downlink Availability

6. (Continued)

6.1 FULL OSCAR SYSTEM MODEL -- PHILOSOPHY AND FLOW CHARTS

This section explains the basic approach used in developing the architecture for the Full OSCAR System Model (FOSM), and presents a flow chart showing the overall interrelationship of the analysis discussed in Section 6.3 and its required inputs. (These inputs are discussed in more detail in Section 6.2.)

6.1.1 Philosophy of Approach -- Full OSCAR System Model (FOSM)

This model, when fully implemented and verified, will be a model of the complete OSCAR system. At this time, only the overall architecture of the FOSM has been developed. In developing this architecture we have used the following approach:

a. The SPDPM is fully available for use as a building block;

b. The DCM is fully available for use as a building block;

c. The baseline option in the DCM is the one most favorable for OSCAR implementation -- i.e., fully adaptive scan;

d. The FOSM requires inputs in the categories of environment, requirements and system design.

e. The environmental inputs include the time varying data bases of cloud parameters, air-water interface parameters, and water parameters.

f. The requirements inputs include system effectiveness parameters.

g. The system design parameters include the details of all aspects of the system, from ground station through satellite orbits through submarine terminals.

h. The system performance over a given set of time intervals is calculated for a given system design using the sub-models included herein. If suitable system performance is not achieved, the system design is modified and the system performance calculated again. If suitable system performance is achieved over a given set of time intervals, then the results are combined with those over other time intervals, so that the system performance over the system lifetime is estimated. If this lifetime performance is not suitable, the system design is iterated, and the process repeated until the system performance matches the requirements.

6.1.1 (Continued)

i. The downlink availability is the driver of total system effectiveness. At this stage of the overall OSCAR program, the SPDPM is composed of unverified propagation models, the DCM inputs include uncertain parameters, and the technology to be used in the OSCAR system is in the R&D stage. Therefore, the downlink availability is calculated to the limits of our present day knowledge, and reasonable requirements are imposed on the remaining contributors to system effectiveness so that the system specification is met.

Implementation of this approach is discussed in Section 6.4, and exemplary results are presented in Section 3 of Volume IV of this final report.

6.1.2 Model Flow Chart -- Full OSCAR System Model

A top level schematic of the Full OSCAR System Model (FOSM) is shown in Figure 6-1. The input parameters are designated as environment, requirements and system design. All three inputs are used to calculate the downlink performance over many time intervals, which requires a multiple application of the DCM. The environment and system design parameters are used to estimate uplink/crosslink availability, and the system design inputs are then used to calculate equipment availability.* All availabilities are then used to calculate system effectiveness over the same time intervals, and, if no system design iteration is necessary, then performance over the system lifetime is calculated.

*But from (i) above, at present the uplink and equipment availability are not calculated from first principles, but are assigned from the downlink result.

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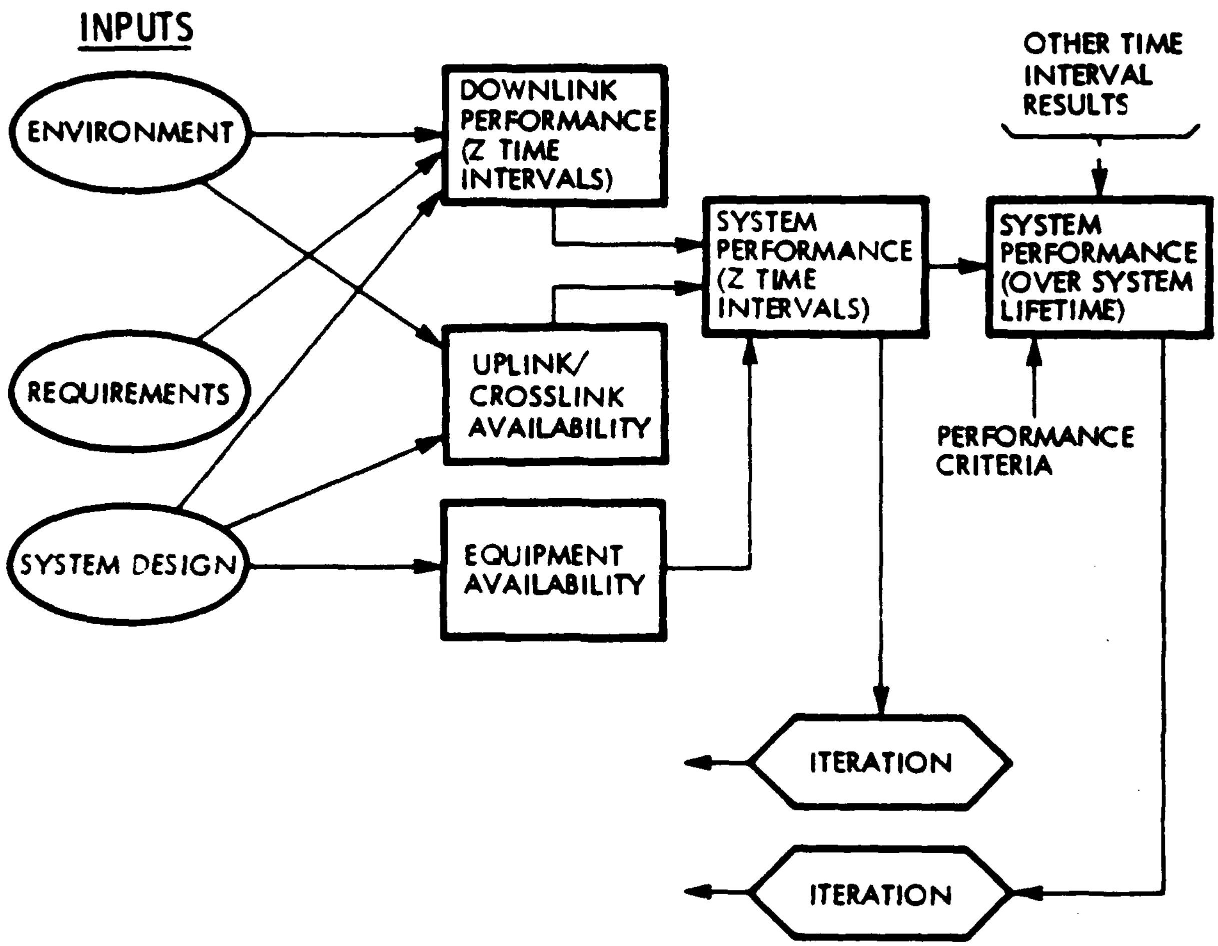


Figure 6-1. Complete Model-Flow Chart

6.2 INPUT INFORMATION

The inputs to the FOSM are divided into Environment, Requirements and System Design. This section discusses eacn of these three kinds of inputs.

6.2.1 Environment

The Environmental inputs to the FOSM are composed of fixed data bases, data bases with predictable variations and data bases with unpredictable variations. Each type has extensive inputs for the Full OSCAR System Model.

6.2.1.1 Fixed Data Bases

The fixed data bases include the operational area coverage, the astronomical distances (since we ignore monthly and seasonal changes in R_{SU} and R_{MU}), the choice of Environmental Resolution Elements, the Skylight/Starlight strength, and ocean depth within the coverage area. Some of these data bases were previously used in the SPDPM. Other and new environmental parameters include:

SYMBOL	DESCRIPTION	UNITS
α_i, β_j	Mean latitude and longitude of all the ERE's within the coverage area.	degrees
$D_{oc\ ij}$	Mean ocean depth of ijth ERE. This enters in when $D_{oc\ ij} \geq D$.	meters

6.2.1.2 Data Bases with Predictable Variations

The data bases with predictable variations include the solar latitude and longitude, the lunar latitude, longitude and phase, and the locations of the ice. Some of these data bases were previously used in the SPDPM and DCM, including L_s, L_m, α_{SU}, β_{SU}, α_{MU}, and β_{MU}.

Other and new environmental parameters include:

SYMBOL	DESCRIPTION	UNITS
ϕ_{PM}	Phase of the moon, which determines its relative strength.	degrees
t	Time of day at Greenwich (0 degrees longitude)	hours

6.2.1.2 (Continued)

SYMBOL	DESCRIPTION	UNITS
	TIME AFTER WINTER SOLSTICE	days
t_{mo}	Time after full moon	days
t_{nm}	Time after sunset	hours
ϕ_o	Lunar latitude at sunset of a given day	degrees
IC_{ij}	Fraction of the ijth resolution element which is covered by ice.	--

6.2.1.3 Data Bases with Unpredictable Variations

The data bases with unpredictable variations include the cloud conditions, the air-water interface conditions, the water conditions and the strength of the bioluminescence. Parts of these data bases have been used in the SPDPM and DCM, including: T, σ_c, <cosθ>, ω_o, θ and H for the clouds for each ERE; n and V for the air-water interface for each ERE; n, k_i, D_i, θ_{SI}, and S for the water for each ERE; and L_{BL} for the bioluminescence for each ERE.

Of these thirteen parameters, the most important ones with unpredictable temporal and spatial variations are T and σ_c for the clouds, V for the air-water interface, k_i and D_i for the water, and L_{BL} itself for the bioluminescence.

New inputs include:

SYMBOL	DESCRIPTION	UNITS
$MTBF_c$	Mean time between environmental conditions which are sufficient to cause an outage.	hours
$MTTR_c$	Mean time for outage-causing conditions to clear.	hours

6.2.2 Requirements

The Full OSCAR System Model uses the complete OSCAR requirement set as its requirements inputs. Some of these have previously been used in the SPDPM and DCM, including T_A, M_{LO}, N_M, N_{SPi}, N_{Ji}, g and D. The rest of the requirements are:

a. Full operational area coverage, specified in terms of α_i, β_j, for the ERE's.

b. No submarine motion constraint (speed or direction);

c. System Effectiveness, specified in terms of a total system availability E_{ff} (syst). Also important are T_{AV}, the time over which the availabilities are averaged in order to obtain E_{ff} (SYST), and P_{EN}, the penalty time for an outage of any portion of the link.

6.2.3 System Design Inputs

The required system design inputs include Ground Station, Satellite, and Submarine Terminal information.

6.2.3.1 Ground Station

The microwave ground stations were not considered at all in the SPDPM nor the DCM because those models only involve the downlink. Therefore, all the inputs are new, and consist of:

SYMBOL	DESCRIPTION	UNITS
B_u	Number of bits to be conveyed on the uplink, per single time interval	bits
B_c	Number of bits to be conveyed on the crosslink, per single time interval	bits
B_B	Number of bits to be conveyed on the backlink, per single time interval	bits
t_u	Time allowed for uplink delivery of bits	seconds
t_c	Time allowed for crosslink delivery of bits	seconds
t_B	Time allowed for backlink delivery of bits	seconds
λ_{RF}	Wavelength corresponding to center RF frequency	meters
P_S	Satellite transmitter power	watts
P_G	Ground station transmitter power	watts

6.2.3.1 (Continued)

SYMBOL	DESCRIPTION	UNITS
$P_J G_J$	Effective jammer radiated power	watts
η_S	Satellite antenna efficiency	--
η_G	Ground station antenna efficiency	--
α_J	Latitude of jammer	degrees
β_J	Longitude of Jammer	degrees
α_{GS}	Latitude of ground station	degrees
β_{GS}	Longitude of ground station	degrees
T_{SUN}	Noise temperature of the sun	^{o}Kelvin
T_{EARTH}	Noise temperature of the earth	^{o}Kelvin
$T_{RECEIVER}$	Noise temperature of the receiver	^{o}Kelvin
T_{RAIN}	Noise temperature of the rain	^{o}Kelvin
W	Extent of Spread Spectrum	Hz
$\left(\frac{E_{RF}}{N_o}\right)_c$	Critical $\left(\frac{\text{Energy per bit}}{\text{Noise Power per Hertz}}\right)$	$\frac{\text{cycles}}{\text{bit}}$
n_{RF}	Number of ground sites per satellite	--
D_S	Satellite antenna diameter	meters
D_G	Ground Station antenna diameter	meters
R_{JG}	Distance from jammer to Ground Station	meters
A_{UL}	Uplink availability	--
MTBF	Mean time between failure	hours
MTTR	Mean time to repair	hours

6.2.3.2 Satellites

Some inputs for the satellites were previously used in the SPDPM and the DCM, but primarily for a single time interval. The invariant satellite inputs are R_{SU}, R_{MU}, $t_{s\ell}$, t_w, PRF, m, E_p, F_L, R_e, $P'_{L\ HO}$, t_f, ℓ, q, γ_T, ϵ, MARG, $\Delta\lambda$, θ_{TS}, θ_{TDR} and choice of the scanning approach.

Additional, and new inputs are:

SYMBOL	DESCRIPTION	UNITS
P'_{TOT}	Total prime power capability of the satellite	watts
T_{ORB}	Period of the orbits	hours
ϵ_e	Eccentricity of the (elliptical) orbit	--
t_p	Time when perigee of the orbit was traversed	hours
ω	Argument of perigee	degrees
i	Inclination angle	degrees
Ω	Right ascension of the ascending node	degrees
Ω_{OR}	Rotation rate of the earth	degrees/second (radians/second)
n	Number of satellites in single ground track	--
ν	Optical frequency	Hz
λ	Optical wavelength	meters
ϕ_{GS}	Latitude of Ground Station	degrees
θ_{GS}	Longitude of Ground Station	degrees
ϕ_S	Latitude of jammer	degrees
θ_S	Longitude of jammer	degrees
Revisits	Number of times a given spot is revisited	--
MTBF	Mean time between failures	hours
MTTR	Mean time to repair (or replace)	hours

6.2.3.3 Submarine Terminals

Most of the system design inputs for the submarine terminal have already been listed in the SPDPM and DCM sections, including θ_R, D, γ_R, d, B_{OPT}, (kT), F_a, G, ($\eta e/h\nu$), R_L, I_d, F, G_{EL}, G_{AZ}, $t_{s\ell}$, demodulation approach, and post-detection processing for time-of-peak demodulation.

Other and new inputs are:

SYMBOL	DESCRIPTION	UNITS
$MTBF_{SUB}$	Mean Time Between Failure	hours
$MTTR_{SUB}$	Mean Time to Repair	hours

6.3 ENVIRONMENT, REQUIREMENTS AND SYSTEM DESIGN CONSIDERATIONS

This section discusses the analysis to be used in the Full Oscar System Model architecture, except for those previously developed in Sections 3 and 4 (the SPDPM), and Section 5 (the DCM).

Section 6.3.1 considers models for the predictable environmental data bases, including sun, moon and ice location.

Section 6.3.2 discusses models for system effectiveness and life cycle cost.

Section 6.3.3 describes the system design analyses relating to the orbits, dynamic effects, line-of-sight, RF link analysis, area allocations, and remote sensor performance for both the submarine and the satellite.

6.3.1 Environment

The sub-models for the data bases only correspond to data bases with predictable spatial and temporal variations. (The fixed data bases are numbers input to other models, while the unpredictable data bases are not suitable for modeling due to their unpredictability.*)

6.3.1.1 Solar Location

The solar contribution to the optical background is characterized by:

$\theta_{S/2}$: The half-angle subtended by the sun at the earth,

L_S: Effective exo-atmospheric radiance of the sun;

R_{SU}: Distance from the sun to the receiver;

λ_{SU}: Solar latitude;

β_{SU}: Solar longitude.

To the accuracies required by the SPDPM, DCM and FOSM, the first three parameters are taken as invariable, and equal to:

$$\theta_{SU} = 4.65\ (10^{-3})\ \text{radians}$$
$$L_S = 635.62\ \text{watts}/((m^2\ (\text{srad})\ \mu m))$$
$$R_{SU} = 1.497\ (10^{11})\ \text{meters.}$$

The solar latitude and longitude are key to estimates of the solar zenith angle for a given environmental resolution element, as shown in equation (5-6) of Section 5.3.1 of this report. However, they do not have to be modelled with extreme accuracy since the P_{SU} and NEP_B are fairly insensitive to changes in solar zenith angle of $\pm 2.5^0$.

We therefore consider simple models, and separate the latitude and longitude.

*Future work may change the categorization of some of these unpredictable data bases to predictable, and hence model-suitable, ones.

6.3.1.1 (Continued)

For the longitude (degrees east of Greenwich), the sun is modelled as going around the earth once in 24-hours (to our accuracy), so we take

$$\boxed{\beta_{SU} = 360\left[1 - \frac{t}{24}\right]} \qquad (6\text{-}1)$$

for t = time, measured in hours after high noon at 0^0 longitude (Greenwich).

For the latitude, the extreme and mean are well known, so that

α_{SU} = 0^0, vernal equinox

= 23.5^0, summer solstice

= 0^0, autumnal equinox

= -23.5^0, winter solstice.

Considering the accuracy required (and to minimize computational time), we use Table. 6-1 as the solar latitude model.

Table 6-1. Solar Latitude Model

DAYS AFTER WINTER SOLSTICE	α_{SU} (DEGREES)
0	-23.5
30	-21
61	-12
91 (Equinox)	0
121	+12
152	+21
192 (Summer Solstice)	+23.5
222	+21
253	+12
283 (Equinox)	0
314	-12
335	-21
Values between those shown are linearly interpolated.	

6.3.1.2 Lunar Location and Phase

The lunar contribution to the optical background is characterized by:

$\theta_{m/2}$: The half-angle subtended by the moon at the earth;

L_m: Effective exo-atmospheric spectral radiance of the moon;

R_{mu}: Distance from the moon to the receiver;

α_{mu}: Lunar latitude;

β_{mu}: Lunar longitude.

To the accuracies required by the SPDPM, DCM and FOSM, the first and third parameters are taken as invariable, and equal to:

$\theta_{m/2} = 4.65\ (10^{-3})$ radians;

$R_{mu} = 3.83\ (10^{8})$ meters.

The value of L_m used in the SPDPM was 1.37 (10^{-3}) watts/((meters)^2 (srad) (meter)), corresponding to a full moon in the blue-green spectral region. For any but a full moon the magnitude of L_m is reduced. The magnitude of L_m depends on the phase angle, α_{pm}, as defined in Figure 6-2.

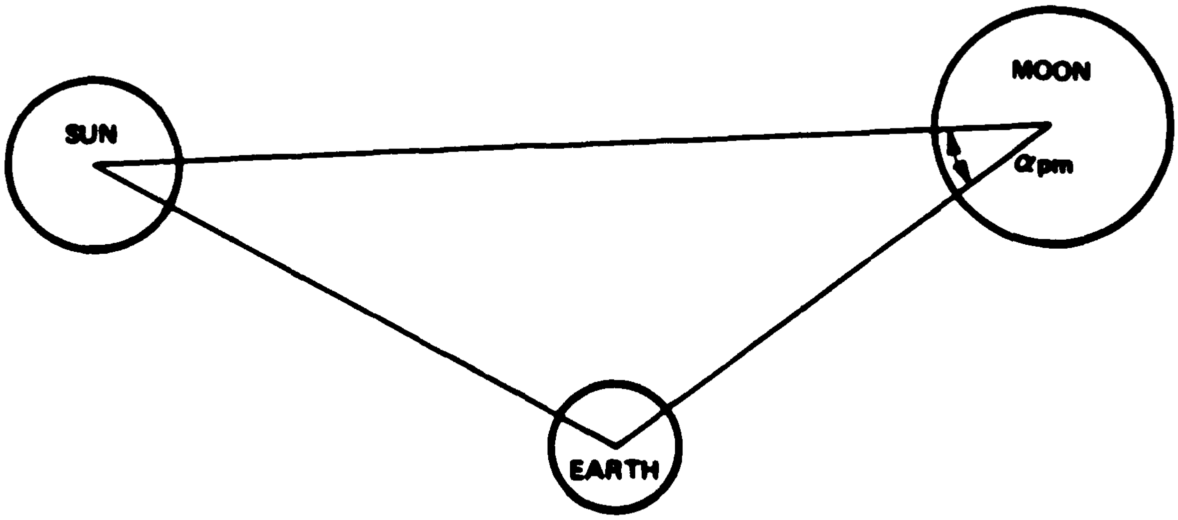


Figure 6-2. Definition of Lunar Phase Angle, α_{pm}

6.3.1.2 (Continued)

To the accuracy required here, we take α_{pm} to linearly go through 360^0 in 27.5 days, so that

$$\alpha_{pm} = 360\left(\frac{t_{mo}}{27.5}\right) \qquad (6\text{-}2)$$

for t_{mo} measured in days, and corresponding to time after full moon.

No analytic model* exists to relate L_m to α_{pm}, so we use the empirically derived result in Table 6-2, and the equation:

$$\boxed{L_m = 1.37\ (10^{-3})\ \bar{T}_m} \qquad (6\text{-}3)$$

Table 6-2. Lunar Brightness as a Function of Phase Angles

LUNAR BRIGHTNESS AS A FUNCTION OF PHASE ANGLE			
α_{pm} (DEGREES)	$\bar{T}_m$	α_{pm}	$\bar{T}_m$
0	1		
5	0.88	75	0.12
10	0.78	80	0.1
15	0.69	85	0.09
20	0.61	90	0.08
25	0.55	95	0.07
30	0.48	100	0.06
35	0.43	105	0.05
40	0.37	110	0.045
45	0.33	115	0.04
50	0.28	120	0.035
55	0.24	130	0.025
60	0.2	140	0.01
65	0.17	150	0
70	0.14		

*Z. Kopal, "An Introduction to the Study of the Moon," Gordon and Breech, (New York, 1966) Chapter 17.

6.3.1.2 (Continued)

The lunar latitude and longitude are key to estimates of the lunar zenith angle for a given environmental resolution element, as shown in equation (5-7) of Section 5.3.1 of this report. However, they do not have to be modelled with extreme accuracy since the P_{mu} and NEP_B are fairly insensitive to changes of lunar zenith angles.

We therefore consider simple models, and separate the latitude and longitude.

For the longitude, again in degrees east of Greenwich, the earth rotates 360^{o} while the moon is moving approximately 1/28 (360) = 12.9^{o} in its orbit around the earth. Over one night, the inaccuracy in completely neglecting lunar motion is taken as negligible and for each night we take

$$\boxed{\beta_{mu} = \beta_{o}\left(1 - \frac{t_{nm}}{24}\right)} \qquad (6\text{-}4)$$

for β_o = initial longitude of the moon at sunset,* and

t_{nm} = time after sunset, measured in hours.

For the latitude, we use the fact that the plane of the moon-earth orbit is inclined at approximately 5.1^{o} to the ecliptic, the plane of the earth-sun orbit. Therefore, we take

$$\boxed{\lambda_{mu} = \lambda_{su} + 5.1^{o}} \qquad (6\text{-}5)$$

as our approximate model for the lunar latitude.

6.3.1.3 Ice Locations

A few of the environmental resolution elements are far enough North that a fraction of their area is covered by ice during the winter and spring months. We model this as completely blanking the OSCAR communication downlink for that fraction of the area. The key parameter is:

---

*β_o should be provided by a separate input, so that the approximation errors in equation (6-4) are not compounded from night to night.

6.3.1.3 (Continued)

IC_{ij}: Fraction of ij[th] resolution element covered by ice. IC_{ij} will be provided in a look-up table in Volume IV of this final report. We do not present it here so that the unclassified nature of this volume may be sustained.

6.3.2 System Effectiveness and Life Cycle Cost Models

This section discusses models for the system effectiveness in terms of link availability, and the life cycle cost model.

6.3.2.1 System Effectiveness

The full OSCAR system may be depicted as a communication tree where the message originates at the ground stations (relatively few in number), is transmitted through the uplink to the satellite, and then through downlinks to the submarines.* Such a tree is represented in Figure 6-3, with the system elements shown.

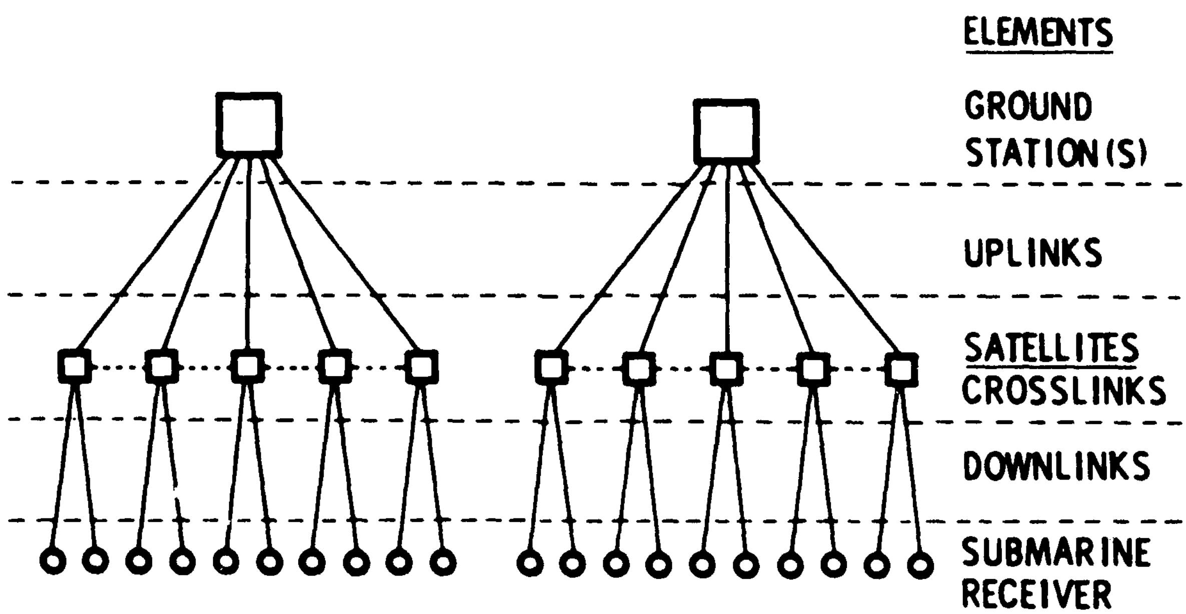


Figure 6-3. System Effectiveness Communication Tree

*Crosslinks between satellites, if used, would not destroy this analogy.

6.3.2.1.1 Basic Definition

Using the communication tree, it is seen that an end-to-end link can be traced from each submarine back to a ground station. Therefore, the number of complete links will equal the number of submarines, and the r^{th} link will have an availability:

$$A_L(r) = A_{GS}(r)A_{UL}(r)A_{SAT}(r)A_{CL}(r)A_{DL}(r)A_{SB}(r). \tag{6-6}$$

The availabilities used are for the appropriate element in the link e.g., that of the ground station and that of the satellite which services that particular submarine, and are defined as:

A_{GS} = ground station availability,

A_{UL} = Uplink availability,

A_{SAT} = satellite availability,

A_{CL} = crosslink availability, including relay equipment on satellites,

A_{DL} = downlink availability,

A_{SB} = submarine receiver availability.

System effectiveness is defined as the average end-to-end link availability:

$$E_{ff}(syst) \doteq \bar{A}_L. \tag{6-7}$$

This can be written in the expanded form.

$$E_{ff}(syst) = \frac{1}{N_L} \sum_{r}^{N_L} A_{GS}(r)A_{UL}(r)A_{SAT}(r)A_{CL}(r)A_{DL}(r)A_{SB}(r) \tag{6-8}$$

Because of the construction of the tree, this equation can be expanded in the following form:

6.3.2.1.1 (Continued)

$$E_{ff}(syst)=\frac{1}{N_L}\Big\{A_{GS}(1)\Big[A_{UL}(1)A_{SAT}(1)A_{CL}(1)\Big(A_{DL}(1)A_{SB}(1)+A_{DL}(2)A_{SB}(2)+\ldots\Big)$$
$$+A_{UL}(2)A_{SAT}(2)A_{CL}(2)\Big(A_{DL}(i)A_{SB}(i)+A_{DL}(i+1)A_{SB}(i+1)+\ldots\Big)$$
$$+A_{UL}(j)A_{SAT}(j)A_{CL}(j)\Big(A_{DL}(k)A_{SB}(k)+A_{DL}(k+1)A_{SB}(k+1)+\ldots\Big)\Big]$$
$$+A_{GS}(2)\Big[A_{UL}(m)A_{SAT}(m)A_{CL}(m)\Big(A_{DL}(n)A_{SB}(n)+A_{DL}(n+1)A_{SB}(n+1)+\ldots\Big)$$
$$+A_{UL}(m+1)A_{SAT}(m+1)A_{CL}(m+1)\Big(A_{DL}(p)A_{SB}(p)+\ldots\Big)\Big]\Big\} \quad (6\text{-}9)$$

If the availability of any individual system element is the same as any other element of the same type, then the expression for system effectiveness reverts to the much simplier form:

$$\boxed{E_{ff}(syst) = \bar{A}_{GS}\bar{A}_{UL}\bar{A}_{SAT}\bar{A}_{CL}\bar{A}_{DL}\bar{A}_{SB}} \quad (6\text{-}10)$$

Moreover, if the availability of like elements is identical, then the mean link availability is equivalent to any individual element availability.

6.3.2.1.2 Downlink Availability

The "downlink" availability requires special mention. Although at any time the number of downlinks equals the number of boats, the specific location of the boats is not known, even to the appropriate environmental resolution element. Therefore, the downlink availability is averaged over all possible boat locations, which in particular will be the satellite area of responsibility, but in sum would be the entire FBM operational area.

Also since the downlink is tied intimately to weather conditions, water conditions, and signal and background conditions, it is reasonable to average over a time interval sufficient to include a range of these conditions. A one month interval would allow for seasonal variations and permit systems' strategies which optimize for seasonal variations. However, in order to meet the system

6.3.2.1.2 (Continued)

effectiveness specification, the availability should be averaged over at least a year (or multiple seasonal periods, including the appropriate system strategies).

6.3.2.1.3 Crosslink Availability

The crosslink availabilities are most likely to be those elements which do not have identical values. This is seen from the fact that some end-to-end links may include crosslinks while other end-to-end links may not require them. Therefore a weighted mean is used in the equation for $\bar{A}_{CL}$:

$$\bar{A}_{CL} = \frac{N_{CL}A_{CL} + (N_L - N_{CL})(1)}{N_L} \tag{6-11}$$

where N_{CL} is the number of crosslinks used in the entire system, and the crosslink availability is taken as unity for those links not using crosslinks.

In general, the number of end-to-end links using crosslinks may change during a cycle of the satellite orbits. Therefore, N_{CL} may be a dynamic number, and the average value over a complete cycle will be used.

6.3.2.1.4 Penalty

The specification requires that a penalty be imposed for each outage. This penalty is imposed on the average element availabilities in accordance with the following rule:

$$\boxed{A_{XX} = \frac{1}{1+X}} \tag{6-12}$$

where X is the larger of either

$$(MTTR/MTBF)_{XX}$$

or

$$\frac{T_{av} \quad P_{en}}{(MTBF)_{XX}^{2}}$$

6.3.2.1.4 (Continued)

where T_{av} is the time over which the system effectiveness is averaged, P_{en} is the penalty, MTTR is the mean time to repair, and MTBF is the mean time between failures.

In the case of the downlink, the nomenclature "mean time between failures" and "mean time to repair" is meaningless. The same statistical concepts are retained by assigning the following definitions for links that do not have equipment:

$MTBF_c$ ≡ mean time between conditions which are sufficient to cause outage.

$MTTR_c$ ≡ mean time for these conditions to clear.

For the uplink and downlink, this information must be provided by the environmental data bases, either implicitly or explicitly.

6.3.2.1.5 Sample Calculation

A sample calculation of availability has been performed using the values in Table 6-3, and choosing T_{av}=8700 hours (1 year), P_{en}=1 hour.

TABLE 6-3

Inputs for Sample System Effectiveness Calculations

	GS	UL	SAT	DL	SB
MTBF (hours)	5000	10,000	50,000	400	5000
MTTR (hours)	1	.5	100	12	1

6.3.2.1.5 (Continued)

The mean element availabilities are:

$\bar{A}_{GS} = 0.9965$

$\bar{A}_{UL} = 0.99991$

$\bar{A}_{SAT} = 0.998$

$\bar{A}_{DL} = 0.948$

$\bar{A}_{SB} = 0.9965$

The system effectiveness is then 0.945.

In this example the downlink availability dominates the system effectiveness, as would seem reasonable.

6.3.2.2 Life Cycle Cost Model

The life cycle cost models to be used in the FOSM are

NAVWESA, WEAPON SYSTEM LCC, FLEX 9B and
NAVWESA, EQUIPMENT LCC, FLEX 4B

They have been used by GTE-Sylvania on other NAVY programs.

6.3.3 System Design Analyses

The new system design analyses includes Orbits, Dynamic Effects, Line-of-Sight, RF link analysis, Area Allocation and Remote Sensor Performance.

6.3.3.1 Orbits

The OSCAR satellites are assumed to travel in circular or elliptical orbits around a spherical earth. Any perturbations to these orbits caused by the sun, the moon, atmospheric drag, or the asphericity of the Earth's gravitation field are to be corrected by periodic thrusts from station-keeping rockets. The orientations of the elliptical orbits remain fixed in inertial space (Figure 6-4), and are referenced to the Earth's equatorial plane (Figure 6-5).

6.3.3.1 (Continued)

Time is referenced to the sidereal day, which represents one rotation of the Earth relative to inertial space, rather than to the sun. This differs from a solar day by a factor of 364/365, since the Earth rotates one more time during this year than the number of days in the year. The "hour" used for time is defined as one twenth-fourth of a sidereal day, and the time origin corresponds to the earth's prime meridian pointing in the direction of the vernal equinox. The satellite positions are determined by six orbital parameters (See Figure 6-5 and 6-6):

T_{orb}, the period of the orbit

ϵ_e, the eccentricity of the ellipse,

t_p, time when perigee of the orbit was traversed,

ω, argument of perigee (angle)

i, inclination angle

Ω, right ascension of the ascending node (angle).

For any given time, these are used to obtain the position (R_s, α_s, β_s) and velocity (R_s, α_s, β_s) of the satellite in the spherical fixed earth coordinate system. (This is the system used in the DCM.)

The position and velocity of a satellite moving in a spherically symmetric gravitational field were derived by Kepler:

$$E = \frac{2\,(t-t_p)+\epsilon_e \sin E}{T_{orb}} \qquad (6\text{-}13a)$$

$$a = \left(5080 \; \frac{km}{hr^{2/3}}\right) T_{orb}^{\;2/3} \qquad (6\text{-}13b)$$

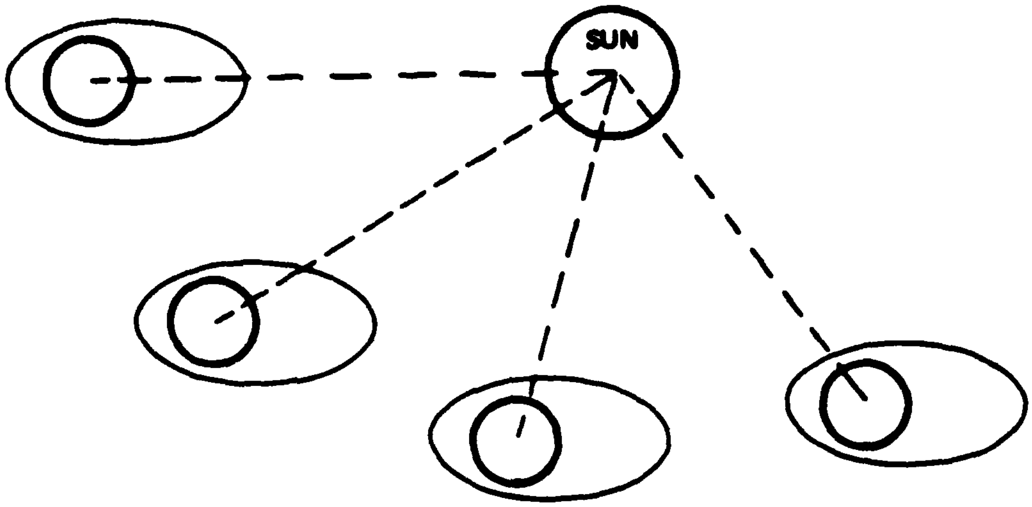


Figure 6-4. Inertially Oriented Orbits

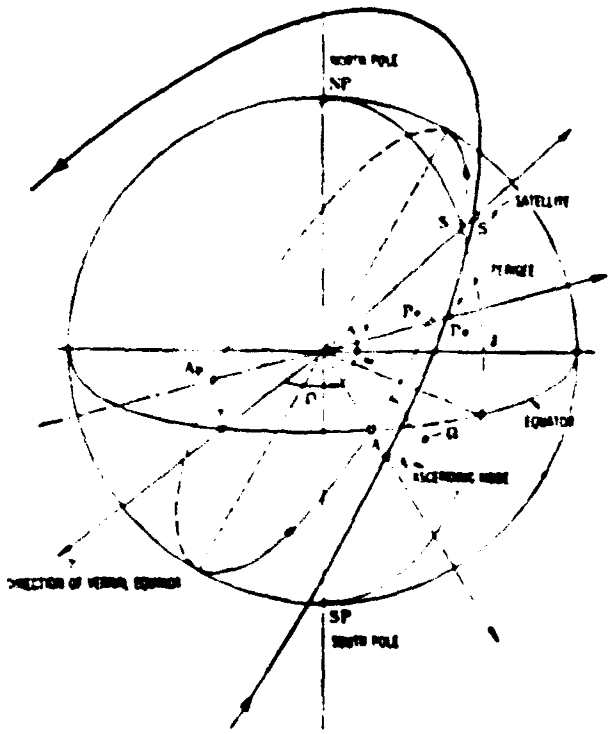


Figure 6-5. Geocentric equatorial coordinates and orbital elements

6.3.3.1 (Continued)

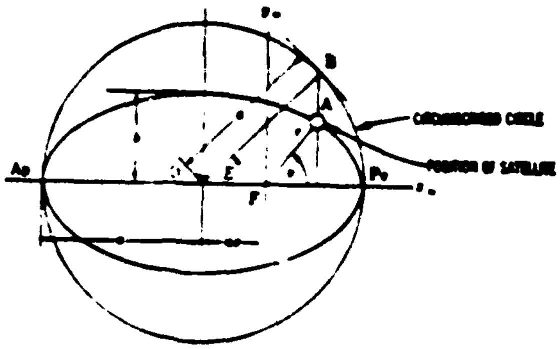


Figure 6-6. Orbital Parameters

$$\left.\begin{aligned} {}^1X &= a(\cos E-\epsilon_e) \\ {}^1Y &= a\sqrt{1-\epsilon_e^2}\,\sin E \\ {}^1Z &= 0 \end{aligned}\right\} \quad (6\text{-}13c)$$

$$\left.\begin{aligned} {}^1\dot{X} &= -\frac{2\pi a\,\sin E}{T(1-\epsilon_e\cos E)} \\ {}^1\dot{Y} &= \frac{2\pi a\sqrt{1-\epsilon_e^2}\,\cos E}{T(1-\epsilon_e\cos E)} \\ {}^1\dot{Z} &= 0 \end{aligned}\right\} \quad (6\text{-}13d)$$

where E is the eccentric anomaly in radians,

a is the semi-major axis in meters,

and the rectangular coordinates $({}^1X, {}^1Y, 0, {}^1\dot{X}, {}^1\dot{Y}, 0)$ are within the plane of the orbit and have their origin at the earth's center (See Figure 6-6). Equation (6-13a), called Kepler's equation, is transcendental and requires and iterative solution.

6.3.3.1 (Continued)

To translate to equatorial plane coordinates requires the following sequence (see Figure 6-5):

a. A rotation of ω about ${}^1Z$ axis.
b. A rotation of i about the ${}^2X$ axis.
c. A rotation of $\Omega+\Omega_{or}t$ about the ${}^3Z$ axis.

These operations are accomplished by successive multiplication of both the position and velocity vectors by the standard rotational matrices of linear algebra:

$$\begin{bmatrix} {}^2X & {}^2\dot{X} \\ {}^2Y & {}^2\dot{Y} \\ {}^2Z & {}^2\dot{Z} \end{bmatrix} = \left[R_3(\Omega+\Omega_{or}t\right] \left[R_1(i)\right]\left[R_3(\omega)\right] \begin{bmatrix} {}^1X_W & {}^1\dot{X}_W \\ {}^1Y_W & {}^1\dot{Y}_W \\ {}^1O_W & {}^1\dot{O}_W \end{bmatrix} \qquad (6\text{-}14)$$

where $$R_1(\alpha) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{bmatrix} \qquad (6\text{-}15a)$$

is a rotation about the X axis (or axis 1) through an angle of α,

$$R_2(\alpha) = \begin{bmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{bmatrix} \qquad (6\text{-}15b)$$

is a rotation about the Y axis (or axis 2), and

$$R_3(\alpha) = \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (6\text{-}15c)$$

is a rotation about the Z axis (or axis 3).

6.3.3.1 (Continued)

The resulting cummulative transformation equations are:+

$$
\left.\begin{aligned}
{}^2X &= {}^1X(\cos(\Omega+\Omega_{or}t)\cos\omega - \sin(\Omega+\Omega_{or}t)\sin\omega\cos i) \\
&\quad -{}^1Y(\cos(\Omega+\Omega_{or}t)\sin\omega + \sin(\Omega+\Omega_{or}t)\cos\omega\cos i) \\
{}^2Y &= {}^1X(\sin(\Omega+\Omega_{or}t)\cos\omega + \cos(\Omega+\Omega_{or}t)\sin\omega\cos i) \\
&\quad +{}^1Y(-\sin(\Omega+\Omega_{or}t)\sin\omega + \cos(\Omega+\Omega_{or}t)\cos\omega\cos i) \\
{}^2Z &= {}^1X\sin\omega\sin i + {}^1Y\cos\omega\sin i
\end{aligned}\right\} \quad \text{(6-17 a,b,c)}
$$

$$
\left.\begin{aligned}
{}^2\dot{X} &= {}^1\dot{X}(\cos(\Omega+\Omega_{or}t)\cos\omega - \sin(\Omega+\Omega_{or}t)\sin\omega\cos i) \\
&\quad -{}^1\dot{Y}(\cos(\Omega+\Omega_{or}t)\sin\omega + \sin(\Omega+\Omega_{or}t)\cos\omega\cos i) \\
{}^2\dot{Y} &= {}^1\dot{X}(\sin(\Omega+\Omega_{or}t)\cos\omega + \cos(\Omega+\Omega_{or}t)\sin\omega\cos i) \\
&\quad +{}^1\dot{Y}(-\sin(\Omega+\Omega_{or}t)\sin\omega + \cos(\Omega+\Omega_{or}t)\cos\omega\cos i) \\
{}^2\dot{Z} &= {}^1\dot{X}\sin\omega\sin i + {}^1\dot{Y}\cos\omega\sin i
\end{aligned}\right\} \quad \text{(6-18 a,b,c)}
$$

The satellite state vector is now referenced to the inertial geocentric coordinate system with the X-axis in the equatorial plane pointing toward the prime meridian, the Y-axis in the equatorial plane, and the Z-axis pointing toward the North pole. To change to the rotating non-inertial system requires subtracting $\vec{\Omega} \times \vec{r}$ from $\dot{\vec{r}}$:

$$
\left.\begin{aligned}
{}^3\dot{X} &= {}^2\dot{X} - (-\Omega_{or}{}^2Y) = {}^2\dot{X} + \Omega_{or}{}^2Y \\
{}^3\dot{Y} &= {}^2\dot{Y} - \Omega_{or}{}^2X
\end{aligned}\right\} \quad \text{(6-19 a,b)}
$$

+ The same equations apply for ${}^3X$, ${}^3Y$ and ${}^3Z$.

6.3.3.1 (Continued)

The satellite state vector is now referenced to the rotating geocentric fixed earth rectangular coordinate system. The following transformation is used to convert between this system and the spherical coordinate system of longitude and latitude:

$$R_s = \sqrt{3_X^2 + 3_Y^2 + 3_Z^2} \quad - R_e \qquad (6\text{-}20a)$$

$$\alpha_s = \tan^{-1} \frac{3_Z}{\sqrt{3_X^2 + 3_Y^2}} \qquad (6\text{-}20b)$$

$$\beta_s = \tan^{-1} \frac{3_Y}{3_X} \qquad (6\text{-}20c)$$

$$\dot{R}_s = \frac{3_X \dot{3}_X + 3_Y \dot{3}_Y + 3_Z \dot{3}_Z}{\sqrt{3_X^2 + 3_Y^2 + 3_Z^2}} \qquad (6\text{-}20d)$$

$$\dot{\alpha}_s = \frac{\dot{3}_Z (3_X^2 + 3_Y^2) - 3_Z (3_X \dot{3}_X + 3_Y \dot{3}_Y)}{\sqrt{3_X^2 + 3_Y^2} \quad (3_X^2 + 3_Y^2 + 3_Z^2)} \qquad (6\text{-}20e)$$

$$\dot{\beta}_s = \frac{3_X \dot{3}_Y - 3_Y \dot{3}_X}{3_Y^2 + 3_Y^2} \qquad (6\text{-}20b)$$

where R_s is the distance from the earth's center to the satellite, β_s is the longitude, and α_s is the latitude. Application of the foregoing transformation from the orbital plane for successive times traces out the ground track of the satellite.

If a stationary ground track is shared by several satellites, it is assumed that the optimal configuration has them equally spaced in time. This requires:

$$t_{pj} = t_{pj-1} - \frac{24}{n} \qquad (6\text{-}21)$$

and

$$\lambda_j = \lambda_{j-1} + \frac{360}{n} \qquad (6\text{-}21)$$

6.3.3.1 (Continued)

where n is the number of satellites, 24 is the orbital period, and t_{pj} and Ω_j are the time of perigee passage and the ascending node angle for the j^{th} satellite.

6.3.3.2 Dynamic Effects

The effects of satellite motion in the FOSM are summarized by the following parameters:

$\theta_S, \dot{\theta}_S$: zenith angle and rate at the earth's surface;

$\phi_{SA}, \dot{\phi}_{SA}$: azimuth angle and rate at the earth's surface;

θ_{SLEW} : angle between 2 satellites as viewed from the earth's surface;

$\dot{R}$: range from a satellite to a point on the earth's surface;

α_{SLEW} : angle between two points on the earth's surface as viewed from the satellite;

$\left(\frac{\Delta\nu}{\nu}\right)$: the relative Doppler frequency shift for a signal between the satellite and the earth's surface;

γ_{SLEW} : angle between a point on the earth's surface and a satellite as viewed from another satellite;

$\left(\frac{\Delta\nu}{\nu}\right)_S$: the relative Doppler frequency shift for signal between two satellites;

$\beta_S, \dot{\beta}_S$: zenith angle and rate for a point on the earth's surface as viewed from inertially oriented satellite-centered coordinate system with its Z axis parallel to the earth's axis and its X axis pointing in the direction of the vernal equinox (See Figure 6-8).

6.3.3.2 (Continued)

$\theta_{SA}, \dot{\theta}_{SA}$: azimuth angle and rate for a point on the earth's surface in the satellite's system (See Figure 6-8).

R_{SS} : distance between 2 satellites.

R_{JS} : distance from jammer to satellite.

These parameters are obtained by conversion of position and velocity from the geocentric fixed earth system to coordinate systems centered on either the satellites or the earth's surface (Figures 6-7 & 6-8). The positions and velocities constitute state vectors for the satellites, submarines, ground stations, jammers, sun, and moon. The satellite state vector in the rectangular fixed earth system, were derived in Section 6.3.3.1 as $({}^3X_3, {}^3Y_3, {}^3Z_3, {}^3\dot{X}_3, {}^3\dot{Y}_3, {}^3\dot{Z}_3)_3$.

The submarines, ground stations, and jammers are at the earth's surface and the submarines are assumed to have negligible speed compared to the satellites. Their state vectors in the spherical fixed earth system are therefore $(R_e, \alpha_{SUB}, \beta_{SUB}, 0, 0, 0)$ for the submarines, $(R_e, \alpha_{GS}, \beta_{GS}, 0, 0, 0)$ for the ground station, and $(R_e, \alpha_J, \beta_J, 0, 0, 0)$ for the jammer. The sun and moon coordinates in the spherical system are $(R_{SU}, \alpha_{SU}, \beta_{SU}, 0, 0, 0)$ and $(R_{MU}, \alpha_{MU}, \beta_{MU}, 0, 0, 0)$.

To determine $\phi_S, \dot{\phi}_S, \phi_{SA}, \dot{\phi}_{SA}, \phi_{SLEW}, \dot{R}$ and $\frac{\Delta\nu}{\nu}$ for a submarine or a ground station located at longitude α and latitude β, the satellite state vector is converted to a system centered at (α, β), in which the Z axis is pointing away from the earth's center, the X axis is pointing South along the meridian, and the Y axis is pointing East (See Figure 6-7). To convert to this system from the rectangular fixed earth system of Section 6.3.3.1, the following operations are required.

- Rotation of position and velocity through an angle of β about axis 3 using matrix (6-15c) of Section 6.3.3.1.
- Rotation of position and velocity through an angle of $(\pi/2)-\alpha$ about axis 2 using matrix (6-15b) of Section 6.3.3.1.
- Translation from earth centered to topo-centered:

$Z = Z - R_e$

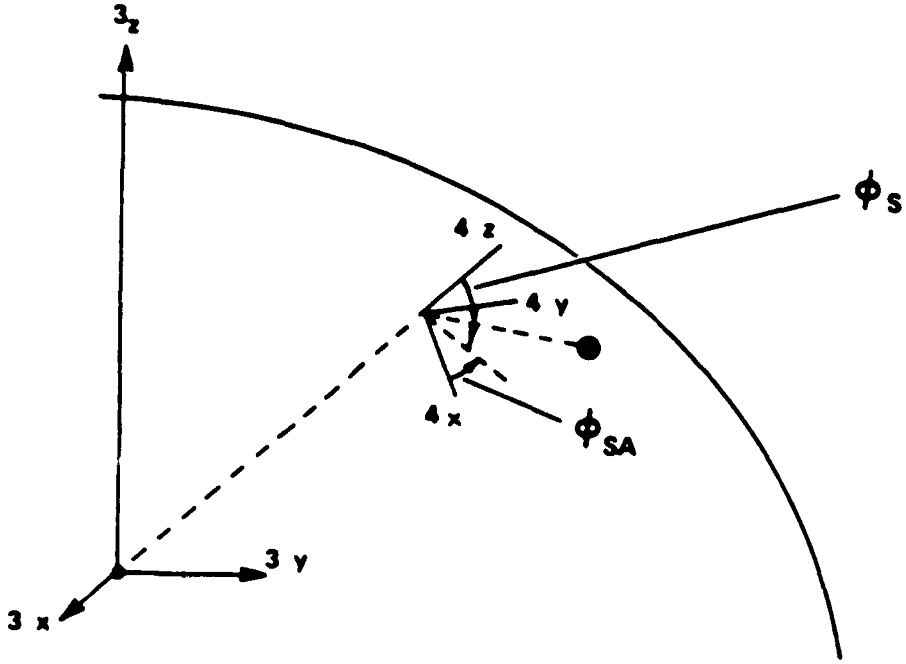


Figure 6-7. Ground Station and Submarine Coordinate System

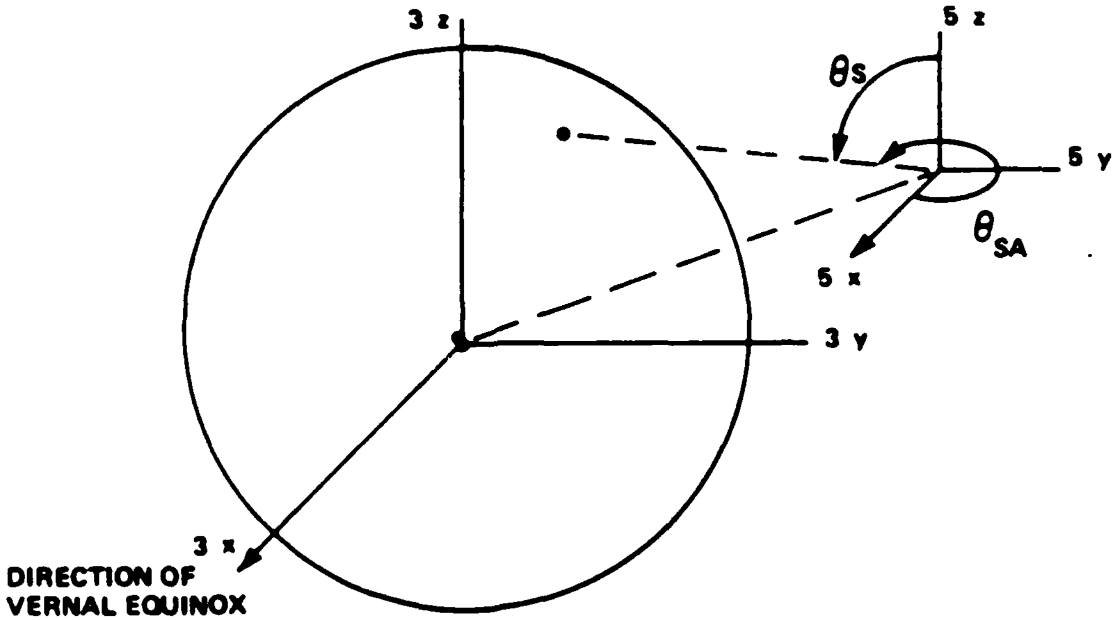


Figure 6-8. Satellite Coordinate System

6.3.3.2 (Continued)

The resulting transformation equations are:

$$^4X = {}^3X \sin\alpha \cos\beta + {}^3Y \sin\alpha \sin\beta - {}^3Z \cos\alpha$$

$$^4Y = -{}^3X \sin\beta + {}^3Y \cos\beta \qquad \text{(6-23 a,b,c)}$$

$$^4Z = {}^3X \cos\alpha \cos\beta + {}^3Y \cos\alpha \sin\beta + {}^3Z \sin\alpha - R_3$$

$$^4\dot{X} = {}^3\dot{X} \sin\alpha \cos\beta + {}^3\dot{Y} \sin\alpha \sin\beta - {}^3\dot{Z} \cos\alpha$$

$$^4\dot{Y} = -{}^3\dot{X} \sin\beta + {}^3\dot{Y} \cos\beta \qquad \text{(6-24 a,b,c)}$$

$$^4\dot{Z} = {}^3\dot{X} \cos\alpha \cos\beta + {}^3\dot{Y} \cos\alpha \sin\beta + {}^3\dot{Z} \sin\alpha$$

where ^3R state vector is derived in Section 6.3.3.1.

The slew angle, ϕ_{SLEW}, at this latitude, α, and longitude, β, between two satellites is now calculated from the vector dot product of the satellite's positions:

$$\boxed{\phi_{SLEW} = \cos^{-1}\left[\frac{^4X_1\,{}^4X_2 + {}^4Y_1\,{}^4Y_2 + {}^4Z_1\,{}^4Z_2}{\sqrt{^4X_1^2 + {}^4Y_1^2 + {}^4Z_1^2}\,\sqrt{^4X_2^2 + {}^4Y_2^2 + {}^4Z_2^2}}\right]} \qquad \text{(6-25)}$$

The rectangular coordinates are converted to the spherical coordinate system shown in Figure (6-9) by using the following equations:

$$R = \sqrt{^4X^2 + {}^4Y^2 + {}^4Z^2}, \quad \phi_S = \cot^{-1}\frac{^4Z}{\sqrt{^4X^2 + {}^4Y^2}}, \quad \phi_{SA} = \tan^{-1}\frac{^4Y}{^4X} \qquad \text{(6-26 a,b,c)}$$

$$\dot{R} = \frac{^4X\,{}^4\dot{X} + {}^4Y\,{}^4\dot{Y} + {}^4Z\,{}^4\dot{Z}}{\sqrt{^4X^2 + {}^4Y^2 + {}^4Z^2}}$$

$$\dot{\phi}_S = \frac{\left(^4X\,{}^4\dot{X} + {}^4Y\,{}^4\dot{Y}\right){}^4Z - {}^4\dot{Z}\left(^4X^2 + {}^4Y^2\right)}{\sqrt{^4X^2 + {}^4Y^2}\left(^4X^2 + {}^4Y^2 + {}^4Z^2\right)} \qquad \text{(6-27 a,b,c)}$$

$$\dot{\phi}_{SA} = \frac{^4X\,{}^4\dot{Y} - {}^4Y\,{}^4\dot{X}}{^4X^2 + {}^4Y^2}$$

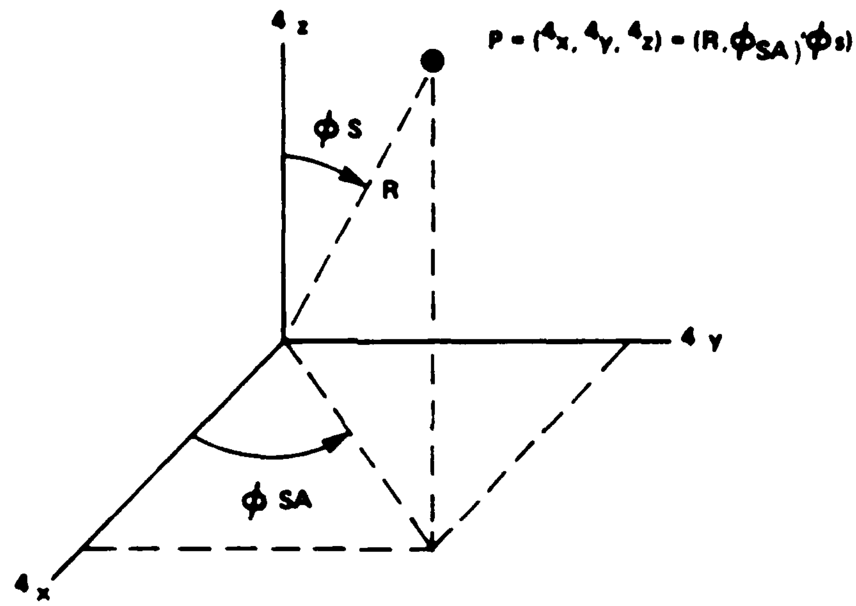


Figure 6-9. Rectangular and Spherical Coordinate Systems Centered on Earth's Surface.

6.3.3.2 (Continued)

The relative Doppler frequency, $(\Delta\nu/\nu)$, is calculated from $\dot{R}$, the rate of change of the range between the satellite and the point on the earth's surface:

$$\left(\frac{\Delta\nu}{\nu}\right) = \frac{\Delta\lambda}{\lambda} = \frac{\dot{R}}{C} \qquad (6\text{-}28)$$

where $\Delta\nu$ and $\Delta\lambda$ are the frequency and wavelength shifts,

ν and λ are the carrier frequency and wavelengths,

and C is the speed of light.

This effect limits the minimum useful bandwidth of nontunable filter and laser combinations to:

$$\boxed{\Delta\lambda_{min} = \frac{\lambda}{C}\left|(\dot{R})_{MAX} - (\dot{R})_{MIN}\right|} \qquad (6\text{-}29)$$

where $\dot{R}_{MAX}$ is the radial velocity leading to the highest Doppler shifted optical frequency,

and $\dot{R}_{MIN}$ is the radial velocity leading to the lowest Doppler shifted optical frequency,

and the algebraic sign of the velocities are preserved.

To determine θ_S, $\dot{\theta}_S$, θ_{SA}, $\dot{\theta}_{SA}$, θ_{SLEW} for the satellite, the state vectors of the ground sites, jammers and submarines are converted to a coordinate system centered on the satellite. The fixed earth state vectors (R_e, θ, α, 0, 0, 0) in the latitude, longitude system are first converted to rectangular coordinates:

$$\left.\begin{aligned} {}^3X_{GS} &= R_e \cos\alpha_{GS} \cos\theta_{GS} \\ {}^3Y_{GS} &= R_e \cos\alpha_{GS} \sin\theta_{GS} \end{aligned}\right\} \qquad (6\text{-}30\ a,b,c)$$

$${}^3Z_{GS} = R_e \sin\alpha_{GS}$$

$${}^3\dot{X}_{GS} = {}^3\dot{Y}_{GS} = {}^3\dot{Z}_{GS} = 0 \qquad (6\text{-}31\ a,b,c)$$

6.3.3.2 (Continued)

$$\left.\begin{aligned} {}^3X_J &= R_e \cos\alpha_J \cos\beta_J \\ {}^3Y_J &= R_e \cos\alpha_J \sin\beta_J \\ {}^3Z_J &= R_e \sin\alpha_J \end{aligned}\right\} \quad \text{(6-32 a,b,c)}$$

$$\left.{}^3\dot{X}_J = {}^3\dot{Y}_J = {}^3\dot{Z} = 0\right\} \quad \text{(6-33 a,b,c)}$$

$$\left.\begin{aligned} {}^3X_{SUB} &= R_e \cos\alpha_{SUB} \cos\beta_{SUB} \\ {}^3Y_{SUB} &= R_e \cos\alpha_{SUB} \mathrm{SIN}\beta_{SUB} \\ {}^3Z_{SUB} &= R_e \sin\alpha_{SUB} \end{aligned}\right\} \quad \text{(6-34 a,b,c)}$$

$$\left.{}^3\dot{X}_{SUB} = {}^3\dot{Y}_{SUB} = {}^3\dot{Z}_{SUB} = 0\right\} \quad \text{(6-35 a,b,c)}$$

The satellite state vector is then subtracted. The resulting vectors are in the system centered at the satellite and rotating with the earth. Since the solar cells must always point toward the sun, the satellite's orientation is assumed to remain (relatively) motionless in inertial space ($\frac{360}{365}$ degrees of rotation per day). Therefore the orientation of the basic satellite system is assumed to be inertial. To convert to this system the state vectors are rotated $-\omega_{or}t$ about axis 3 using matrix 6-15c of Section 6.3.3.1 and $\vec{\Omega}_{or}\times\vec{r}$ is added to the velocity components, $\dot{\vec{r}}$, where Ω_{or} is the rate of rotation of the earth. The transformation equations are:

6.3.3.2 (Continued)

$$\left.\begin{aligned} {}^5X_{GS} &= ({}^3X_{GS}-{}^3X_S)\cos\Omega_{or}t - ({}^3Y_{GS}-{}^3Y_S)\sin\Omega_{or}t \\ {}^5Y_{GS} &= ({}^3X_{GS}-{}^3X_S)\sin\Omega_{or}t + ({}^3Y_{GS}-{}^3Y_S)\cos\Omega_{or}t \\ {}^5Z_{GS} &= {}^3Z_{GS}-{}^3Z_S \end{aligned}\right\} \qquad (6\text{-}36\ a,b,c)$$

$$\left.\begin{aligned} {}^5\dot{X}_{GS} &= ({}^3\dot{X}_{GS}-{}^3\dot{X}_S)\cos\Omega_{or}t - ({}^3\dot{Y}_{GS}-{}^3\dot{Y}_S)\sin\Omega_{or}t \\ {}^5\dot{Y}_{GS} &= ({}^3\dot{X}_{GS}-{}^3\dot{X}_S)\sin(\Omega_{or}t) + ({}^3\dot{Y}_{GS}-{}^3\dot{Y}_S)\cos\Omega_{or}t \\ {}^5\dot{Z}_{GS} &= {}^3\dot{Z}_{GS}-{}^3\dot{Z}_S \end{aligned}\right\} \qquad (6\text{-}37\ a,b,c)$$

$$\left.\begin{aligned} {}^5X_J &= ({}^3X_J-{}^3X_S)\cos\Omega_{or}t - ({}^3Y_J-{}^3Y_S)\sin\Omega_{or}t \\ {}^5Y_J &= ({}^3X_J-{}^3X_S)\sin\Omega_{or}t + ({}^3Y_J-{}^3Y_S)\cos\Omega_{or}t \\ {}^5Z_J &= {}^3Z_J-{}^3Z_S \end{aligned}\right\} \qquad (6\text{-}38\ a,b,c)$$

$$\left.\begin{aligned} {}^5\dot{X}_J &= ({}^3\dot{X}_J-{}^3\dot{X}_S)\cos\Omega_{or}t - ({}^3\dot{Y}_J-{}^3\dot{Y}_S)\sin\Omega_{or}t \\ {}^5\dot{Y}_J &= ({}^3\dot{X}_J-{}^3\dot{X}_S)\sin\Omega_{or}t + ({}^3\dot{Y}_J-{}^3\dot{Y}_S)\cos\Omega_{or}t \\ {}^5\dot{Z}_J &= {}^3\dot{Z}_J-{}^3\dot{Z}_S \end{aligned}\right\} \qquad (6\text{-}39\ a,b,c)$$

$$\left.\begin{aligned} {}^5X_{SUB} &= ({}^3X_{SUB}-{}^3X_S)\cos\Omega_{or}t - ({}^3Y_{SUB}-{}^3Y_S)\sin\Omega_{or}t \\ {}^5Y_{SUB} &= ({}^3X_{SUB}-{}^3X_S)\sin\Omega_{or}t + ({}^3Y_{SUB}-{}^3Y_S)\cos\Omega_{or}t \\ {}^5Z_{SUB} &= {}^3Z_{SUB}-{}^3Z_S \end{aligned}\right\} \qquad (6\text{-}40\ a,b,c)$$

6.3.3.2 (Continued)

$$\left.\begin{aligned}
{}^5\dot{X}_{SUB} &= ({}^3\dot{X}_{SUB} - {}^3\dot{X}_S)\cos\Omega_{or}t - ({}^3\dot{Y}_{SUB} - {}^3\dot{Y}_S)\sin\Omega_{or}t \\
{}^5\dot{Y}_{SUB} &= ({}^3\dot{X}_{SUB} - {}^3\dot{X}_S)\sin\Omega_{or}t + ({}^3\dot{Y}_{SUB} - {}^3\dot{Y}_S)\cos\Omega_{or}t \\
{}^5\dot{Z}_{SUB} &= {}^3\dot{Z}_{SUB} - {}^3\dot{Z}_S
\end{aligned}\right\} \qquad (6\text{-}41\ a,b,c)$$

where $({}^3X_S, {}^3Y_S, {}^3Z_S, {}^3\dot{X}_S, {}^3\dot{Y}_S, {}^3\dot{Z}_S)$ is the state vector of the satellite in the rectangular geocentric fixed earth coordinate system derived in Section 6.3.3.1.

θ_{SLEW} is calculated using the vector dot product:

$$\boxed{\theta_{SLEW} = \cos^{-1} \frac{{}^5X_{SUB1}\,{}^5X_{SUB2} + {}^5Y_{SUB1}\,{}^5Y_{SUB2} + {}^5Z_{SUB1}\,{}^5Z_{SUB2}}{\sqrt{{}^5X^2_{SUB1} + {}^5Y^2_{SUB1} + {}^5Z^2_{SUB1}}\ \sqrt{{}^5X^2_{SUB2} + {}^5Y^2_{SUB2} + {}^5Z^2_{SUB2}}}} \qquad (6\text{-}42)$$

$\theta_S, \dot{\theta}_S, \phi_{SA}, \dot{\phi}_{SA}$ are obtained using the equations for conversion to spherical coordinates:

$$\theta_S = \cot^{-1}\left[\frac{{}^5Z_{SUB}}{\sqrt{{}^5X^2_{SUB} + {}^5Y^2_{SUB}}}\right] \qquad (6\text{-}43)$$

$$\dot{\theta}_S = \frac{({}^5X_{SUB}\,{}^5\dot{X}_{SUB} + {}^5Y_{SUB}\,{}^5\dot{Y}_{SUB})\,{}^5Z_{SUB} - {}^5\dot{Z}_{SUB}\,({}^5X^2_{SUB} + {}^5Y^2_{SUB})}{\sqrt{{}^5X^2_{SUB} + {}^5Y^2_{SUB}}\ ({}^5X^2_{SUB} + {}^5Y^2_{SUB} + {}^5Z^2_{SUB})} \qquad (6\text{-}44)$$

$$\phi_{SA} = \tan^{-1} \frac{{}^5Y_{SUB}}{{}^5X_{SUB}} \qquad (6\text{-}45)$$

$$\dot{\phi}_{SA} = \frac{{}^5X_{SUB}\,{}^5\dot{Y}_{SUB} - {}^5Y_{SUB}\,{}^5\dot{X}_{SUB}}{{}^5X^2_{SUB} + {}^5Y^2_{SUB}} \qquad (6\text{-}46)$$

6.3.3.2 (Continued)

Ψ_{SLEW} is most easily calculated using the vector dot product in rectangular fixed earth coordinates:

$$\boxed{\Psi_{SLEW} = \cos^{-1} \frac{({}^3x_{S2}-{}^3x_{S1})({}^3x_J-{}^3x_{S1})+({}^3y_{S2}-{}^3y_{S1})({}^3y_J-{}^3y_{S1})+({}^3z_{S2}-{}^3z_{S1})({}^3z_J-{}^3z_{S1})}{\sqrt{({}^3x_{S2}-{}^3x_{S1})^2+({}^3y_{S2}-{}^3y_{S1})^2+({}^3z_{S2}-{}^3z_{S1})^2}\sqrt{({}^3x_J-{}^3x_{S1})^2+({}^3y_J-{}^3y_{S1})^2+({}^3z_J-{}^3z_{S1})^2}}} \quad (6\text{-}47)$$

where Ψ_{SLEW} is the angle between satellite 2 and the jammer on the earth's surface as viewed from satellite 1.

R_{SS}, the distance between 2 satellites, and R_{SJ}, the distance between satellite 2 and the jammer, are calculated in the fixed earth coordinate system:

$$R_{SS} = \sqrt{({}^3X_{S2}-{}^3X_{S1})^2 + ({}^3Y_{S2}-{}^3Y_{S1})^2 + ({}^3Z_{S2}-{}^3Z_{S1})^2} \quad (6\text{-}48)$$

$$R_{JS} = \sqrt{({}^3X_J-{}^3X_{S1})^2 + ({}^3Y_J-{}^3Y_{S1})^2 + ({}^3Z_J-{}^3Z_{S1})2} \quad (6\text{-}49)$$

6.3.3.3 Line of Sight Calculation

A line of sight must exist between two satellites before they can communicate using crosslinks, and the sun must be visible to a satellite before it uses its laser (or it will need excessive battery storage). For these reasons the line of sight condition illustrated in Figure 6-10 must be examined. The shaded area is not visible from satellite 1, represented by position vector $\hat{R}_1$. For another satellite or the sun, with position vector $\hat{R}_2$ to be outside of this area,

$$\vec{R}_1 \cdot \vec{R}_2 < \sqrt{R_1^2 - R_e^{\,2}} \quad (6\text{-}50a)$$

or

$$\theta^1 > \theta \quad (6\text{-}50b)$$

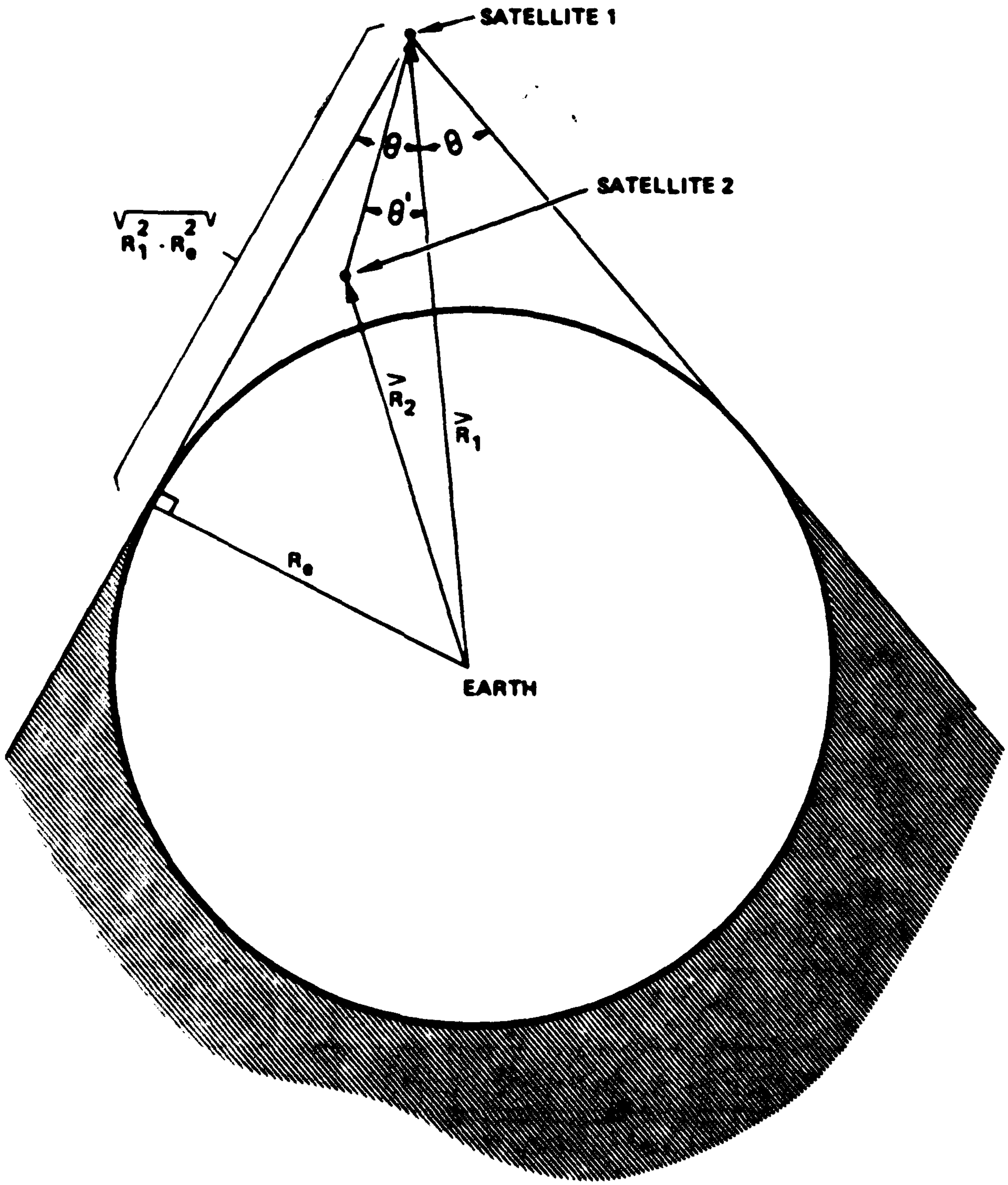


Figure 6-10. Line of Sight Geometry

6.3.3.3 (Continued)

i.e., satellite 2 is visible if it is within $\sqrt{R_1^2 - R_e^2}$ of satellite 1, or if it is outside the cone formed by the satellite and its tangents to the earth. θ^1 is the angle between vector $\vec{R}_1$ and vector $\vec{R}_1 - \vec{R}_2$ and can be calculated using the vector dot product:

$$\theta^1 = \cos^{-1}\left[\frac{(\vec{R}_1-\vec{R}_s)\cdot\vec{R}_1}{|R_1-R_2|\ |R_1|}\right] . \tag{6-51}$$

From Figure 6-10

$$\theta = \sin^{-1}\left(\frac{R_e}{|R_1|}\right) = \cos^{-1}\left(\frac{\sqrt{R_1^2 - R_e^2}}{|R_1|}\right) . \tag{6-52}$$

The second condition then becomes:

$$\boxed{\frac{(\vec{R}_1-\vec{R}_s)\cdot\vec{R}_1}{|R_1-R_2|} < \sqrt{R_1^2 - R_e^2}} . \tag{6-50b}$$

Expressed in the rectangular fixed earth coordinates derived in Section 6.3.3.1 the two conditions become:

$$({}^3X_1-{}^3X_2)^2+({}^3Y_1-{}^3Y_2)^2+({}^3Z_1-{}^3Z_2)^2 < {}^3X_1^2+{}^3Y_1^2+{}^3Z_1^2-R_e^2 \tag{6-53a}$$

$$\frac{({}^3X_1-{}^3X_2)\,{}^3X_1+({}^3Y_1-{}^3Y_2)\,{}^3Y_1+({}^3Z_1-{}^3Z_2)\,{}^3Z_1}{\sqrt{({}^3X_1-{}^3X_2)^2+({}^3Y_1-{}^3Y_2)^2+({}^3Z_1-{}^3Z_2)^2}} < \sqrt{{}^3X_1^2+{}^3Y_1^2+{}^3Z_1^2-R_e^2} \tag{6-53b}$$

6.3.3.3 (Continued)

These can be immediately applied if the satellite position vectors are expressed in any rectangular coordinate system. The sun position is defined in the full system model in terms of the latitude, longitude spherical coordinate system and must be converted using equations (6-20) of 6.3.3.1 before the test. For the sun, the first test is useless. Since the sun is very far away and is in reality an extended light source, the vector difference $\vec{R}_1 - \vec{R}_2$ is approximated by the sun position vector. The second condition then becomes:

$$-\hat{R}_2 \cdot \vec{R}_1 < \sqrt{R_1^2 - R_e{}^2} \qquad (6\text{-}54)$$

where $\hat{R}_2$ is the unit vector in sun's direction. Therefore using equations (6-20) of Section 6.3.3.1, the line of sight condition to the sun becomes:

$$\boxed{{}^3X \cos \alpha_{su} \cos \beta_{su} + {}^3Y \cos \alpha_{su} \sin\beta_{su} + {}^3Z \sin\alpha_{su} > -\sqrt{{}^3X^2 + {}^3Y^2 + {}^3Z^2 - R_e{}^2}} \qquad (6\text{-}55)$$

This will be required for every satellite at the time it is using its laser, and equations (6-53a) and (6-53b) above will be required for every 2 satellites which are using a crosslink.

6.3.3.4 RF Communication Link Analysis

There are three potential RF communication links: an uplink from the ground station to a satellite, a crosslink between satellites, and a link from the satellite back to the ground station (which will be called a backlink). The uplink and backlink share the same frequency band, but the difference in the transmitter powers, data rates, and noise sources requires separate analysis.

Three signal margins (M_u, M_C, M_B), which determine the success of the links, will be derived using the following inputs:

B_u, B_C, B_B: Number of bits for each link to transfer,
t_u, t_C, t_B: Time allowed for each link to transfer data,
λ_{RF}: Wavelength corresponding to RF center frequency,
P_S, P_G: Satellite and ground station transmitter powers,

6.3.3.4 (Continued)

D_S, D_G: Satellite and ground station antenna diameters,

$P_J G_J$: Effective radiated power for a jammer,

η_S, η_G: Satellite and ground station antenna efficiencies,

R_{GS}: The range from the ground site to the satellite,

R_{JS}: The range from the jammer site to the satellite,

R_{GJ}: The range from the jammer site to the ground site,

R_{SS}: The range from one satellite to another,

ϕ_S: The zenith angle to the satellite as measured at the ground site,

A_{UL}: The required availability for the uplink (and backlink)atmospheric channel,

θ_{SLEW}: The angle between a jammer at latitude α_J and longitude β_J and a satellite as viewed from another satellite,

$\tau_{RAIN}, \tau_{RADOME}$: Signal attenuation factors,

$T_{SUN}, T_{EARTH}, T_{RECEIVER}, T_{RAIN}$: Noise temperatures,

W: Spread spectrum bandwidth for signal.

The uplink/backlink model is illustrated in Figure 6-11a where the narrow beam of the satellite antenna's gain profile allows a flat earth approximation for the link's footprint. Both satellite and ground station antennas are used for both transmission and reception of all traffic, including satellite telemetry and control as well as the primary communications. The backlink is needed to carry measurements of critical satellite parameters, remote sensor information, message verification and retransmission requests. Figures 6-11b shows the cross-link model in which satellite 1 is receiving from satellite 2 and from a jammer on the earth's surface.

The signal modulation method for the links will not be specificied except to note Figure 6-12, which indicates that there are several methods for obtaining a bit error rate of less than 10^{-4} with an energy per bit over noise power per hertz (E_{RF}/N_0) of 12 dB. It will be assumed that with error correction or error

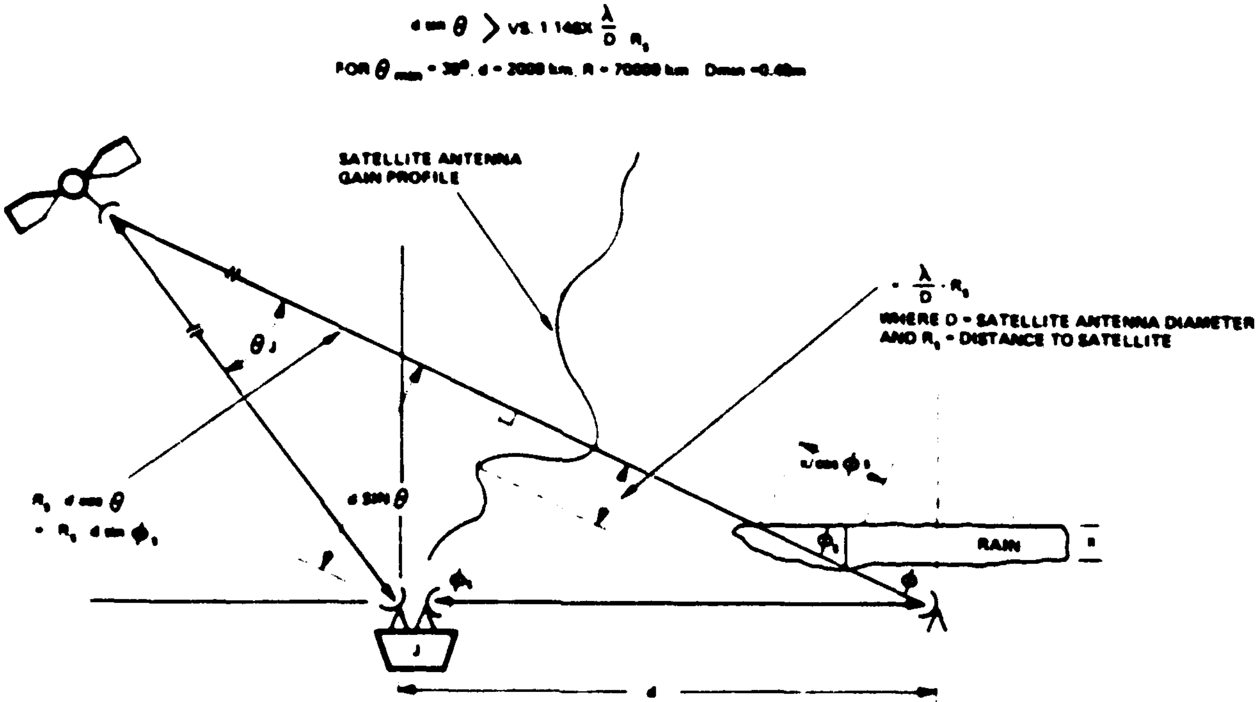


Figure 6-11a. Uplink/Backlink Configuration

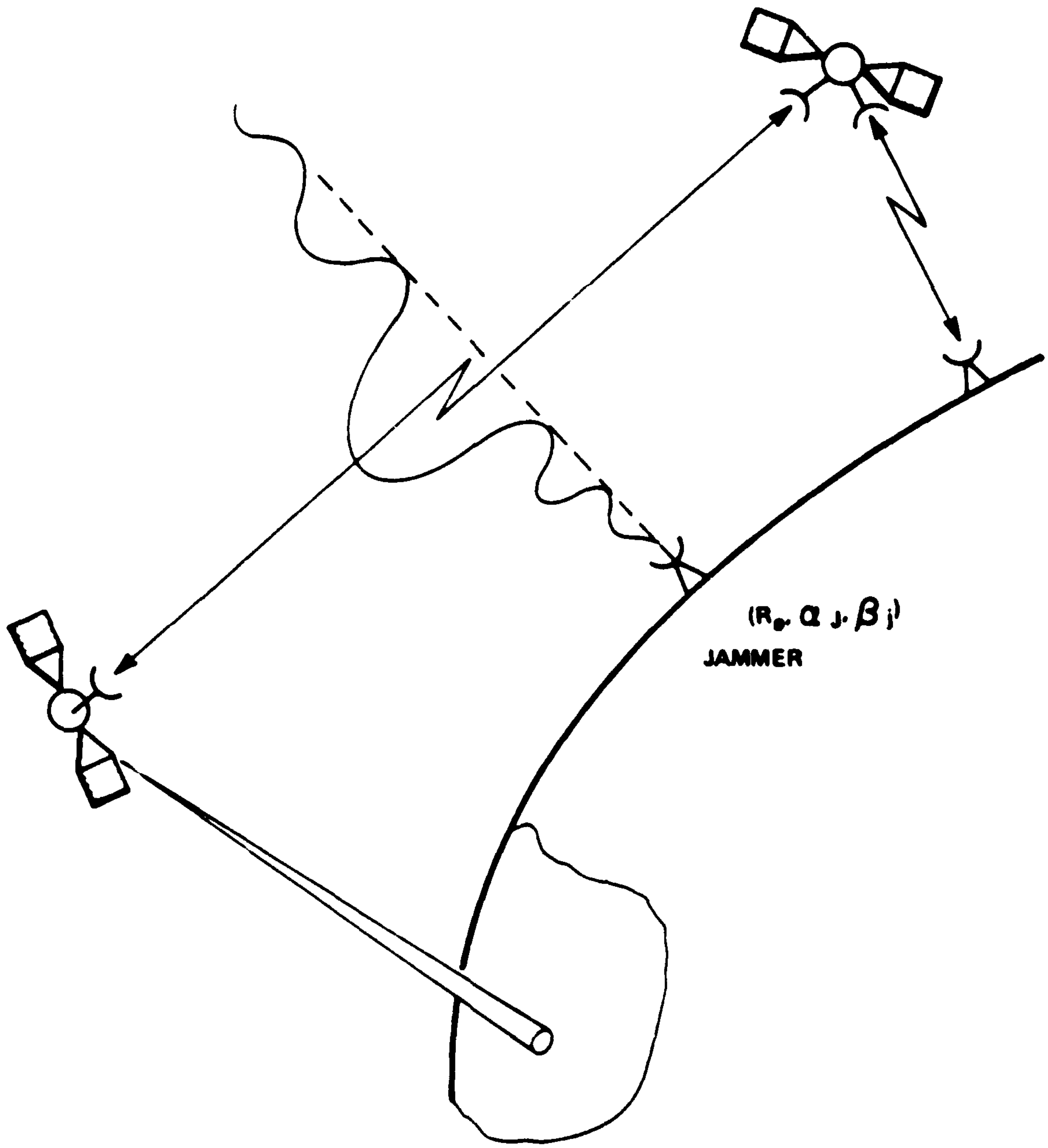


Figure 6-11b. Crosslink Configuration

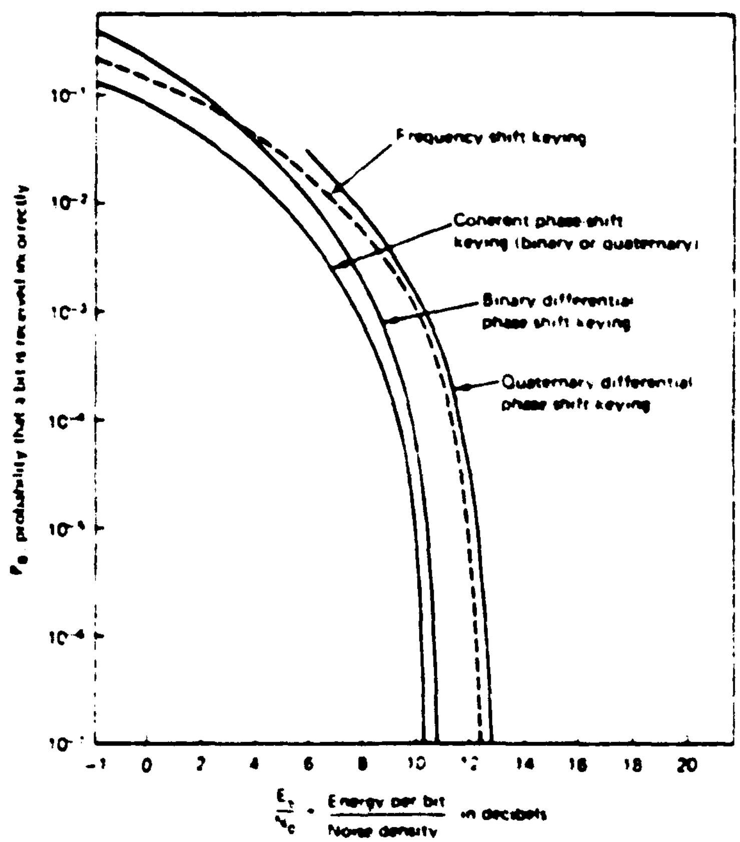


Figure 6-12. Variation in bit error probability with E_b/N_0.

6.3.3.4 (Continued)

detection followed by possible retransmission, this bit error rate is sufficient. For instance, if 10^6 bits were transmitted with single bit error correction for 31 bit blocks, the probability of an uncorrected error would be only 15%. If 10^4 bit blocks were then used for error detection and retransmission, the probability of uncorrected errors after 1 retransmission would only be .0003. Therefore, 12 dB will be used as the critical $(E/N_o)_c$ for successful communication.

$$\left(\frac{E_{RF}}{N_o}\right)_c = 12 \text{ dB} \tag{6-56}$$

and

$$\left(\frac{S_{RF}}{N_o}\right)_c = \left(\frac{E_{RF}}{N_o}\right)_c \left(\frac{B_{RF}}{t_{RF}}\right) \tag{6-57}$$

where E_{RF} is the energy per message bit,
S_{RF} is the signal power at the receiver,
N_o is the noise power per hertz density at the receiver,
B_{RF} is the number of bits in the message,
t_{RF} is the message time interval.

In order to overcome intentional jamming, the signal bandwidth, W, is assumed to be increased by spectrum spreading techniques (pseudo-noise, frequency hopping, time hopping, etc). The form of the margin calculations is as follows:

$$M = \frac{\left(\frac{S_{RF}}{N_o}\right)}{\left(\frac{S_{RF}}{N_o}\right)_c} = \frac{S_{RF}}{N_o} \quad \frac{t_{RF}}{B_{RF}\left(E_{RF}/N_o\right)_c} \tag{6-58}$$

The signal power at the receiver is given by:

$$S_{RF} = P_T{}^{RF} G_T G_R \cdot \left(\frac{\lambda_{RF}}{4\pi R_T}\right)^2 \tau_{Rain} \quad \tau_{Radome} \quad \tau_{Air} \tag{6-59}$$

6.3.3.4 (Continued)

where P_T^{RF} is the transmitter power,

G_T, G_R are the gains of the transmitting and receiving antennas,

λ_{RF} is the RF wavelength,

R_T is the range to the receiver,

and the τ are transmission terms accounting for losses.

This equation assumes there are no antenna pointing errors. Both boresight gains are given by:

$$G = \left(\frac{\pi D_{RF}}{\lambda_{RF}}\right)^2 \quad \eta_{RF} \tag{6-60}$$

where D is the antenna diameter and η is the antenna efficiency, generally about 50%.

The signal expression is valid for both uplink and backlink when the appropriate transmitter power value, P_T^{RF}, is used. It is also valid for the crosslink if the atmospheric attenuation factors are dropped. The term, τ_{RAIN}, is extracted from the rain attenuation statistics for the ground sight for a given availability. Figure 6-13 shows the zenith path attenuation vs. availability for various frequencies for Rosman, North Carolina.

As shown in Figure 6-14, these statistics are typical for East coast stations, and conservative for most West coast stations. They will be used for all ground station models. The large rain attenuation factors are caused by small convection cells, which are several kilometers in diameter, and pass-by in minutes. The probability of encountering one of these cells is assumed to be proportional to the path length through the atmosphere. Therefore, the availability for a non-zenith path is decreased from the zenith path availability used in Figure 6-13, by:

$$A_{UL} = \left(A_{UL,z}\right)^{\sec \theta^{RF}_S} \tag{6-61}$$

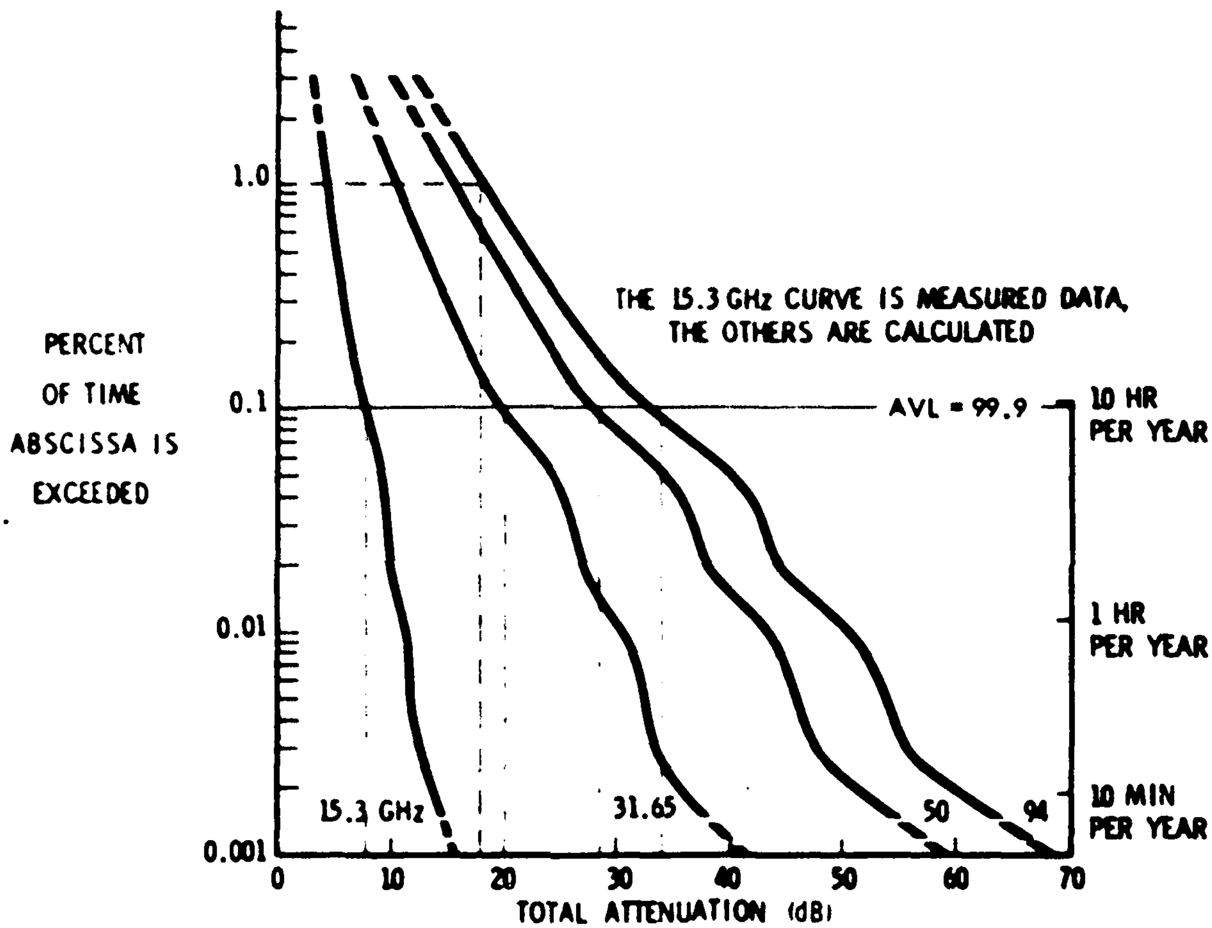


Figure 6-13. Attenuation Distributions for Calendar Year 1970 at Roseman, North Carolina

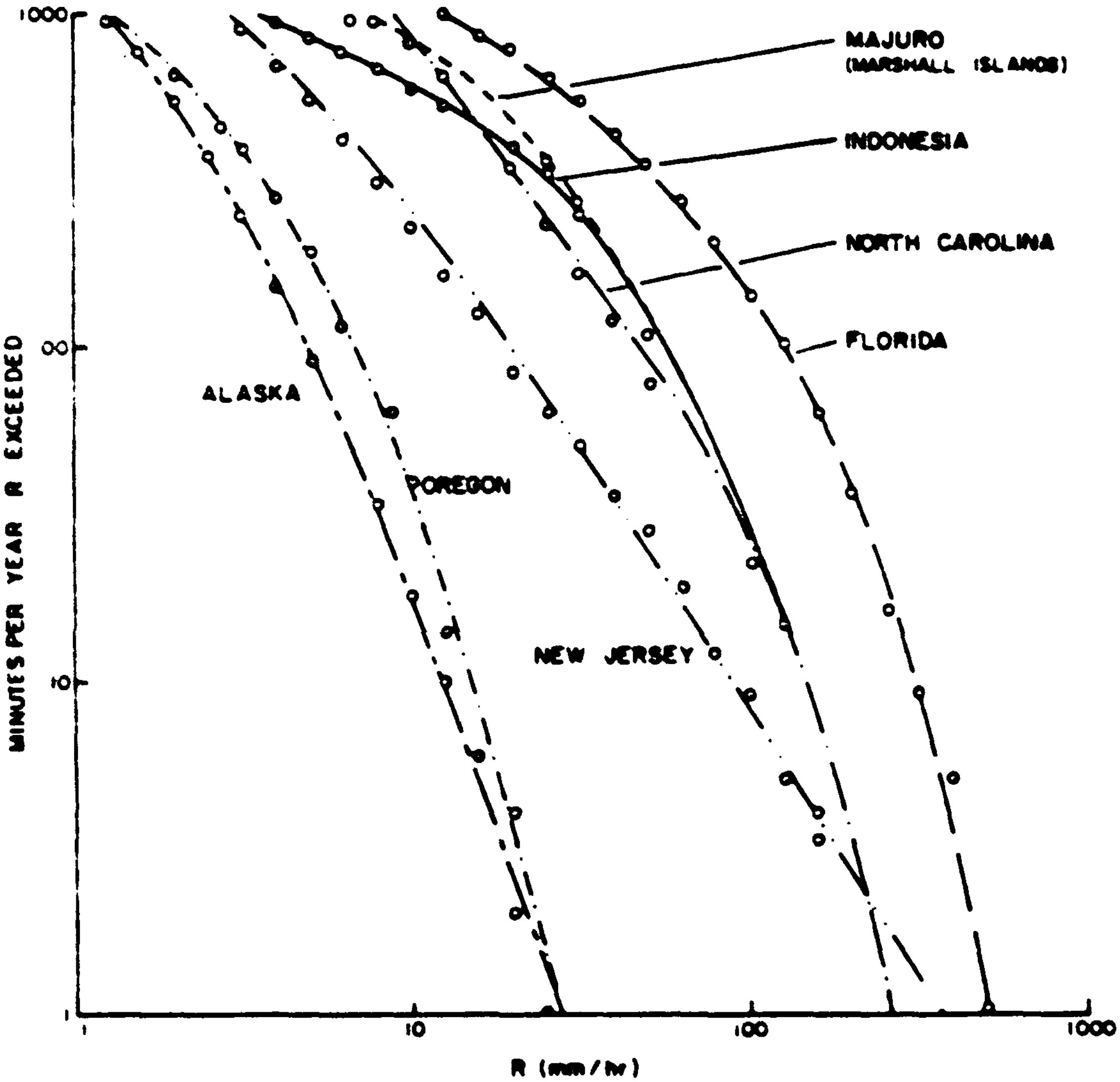


Figure 6-14. Rainfall Intensity Occurrences for Different Geographic Locations

6.3.3.4 (Continued)

where sec ϕ_s^{RF} is the path length factor. If more than one site can communicate with a particular satellite, then the total link availability is increased. The resulting availability from both of these factors is:

$$A_{UL} = 1 - \prod_{si}^{n_{RF}} \left[1 - (A_{UL,Z})^{\sec \phi_{si}^{RF}} \right] \tag{6-62}$$

where n_{RF} is the number of ground sites, which are assumed to be separated enough to have uncorrelated heavy rain statistics.

To use Figure 6-13's statistics for 2 ground stations with different zenith angles to the satellite requires a trial and error approach, which minimizes the maximum attenuation of either site, for a given desired total link availability. If, however, the sites are close enough that the zenith angles are roughly equal, but their rain statistics uncorrelated, then the availability to be used in Figure 6-13 can be calculated:

$$A_{UL,Z} = \left(1-(1-A_{UL})^{1/n_{RF}}\right)^{\cos \phi_s^{RF}} \quad . \tag{6-63}$$

For example, a desired total uplink availability (due to rain) of 99.9% at a zenith angle of 80° is equivalent to a zenith availability of 99.982%, which corresponds to a rain attenuation at 32 GHz of 28 dB (which must be overcome by the transmitter). If two such stations are available, the required zenith availability at each site is only 99.44%, or an attenuation of only 12 dB at 32 GHz.

τ_{RADOME}, the attenutation factor from the ground antenna's radome, if one is used, can be estimated from Figure 6-15 which given a maximum value of 4.2 dB loss for heavy rain onto a dirty radome at 30 GHz.

CURVE	WATER FILM THICKNESS mm	FILMING CONDITIONS (1) [illegible]	[illegible]	[illegible]	[illegible]	NON FILMING CONDITIONS (2) [illegible]	[illegible]	[illegible]	[illegible]
		RAIN RATE mm/hr				RAIN RATE mm/hr			
A	0.0100	1.0	1.4	2.0	3.6	2.8	3.6	4.8	10.2
B	0.0200	1.5	2.0	3.0	6.3	6.0	7.8	12.0	24.4
C	0.0320	2.0	3.0	4.5	9.5	11.5	16.8	24.0	40.2
D	0.0407	3.3	4.5	6.4	13.1	23.5	32.0	48.5	100.0
E	0.0463	4.0	5.4	8.3	16.7	35.5	48.5	72.5	
F	0.0584	6.3	8.0	12.3	25.8	76.2	100.0	100.0	
G	0.080	10.0	13.5	20.5	42.0	100.0			

Z DRY RADOME ESSCOLAM 6 MEMBRANE THICKNESS = 0.8130 mm (0.032 in)

NOTES (1) [illegible] FORMULA THEORETICAL TURBULENT FLOW (2) ESSCO FORMULA EXPERIMENTAL
(3) WATER FILM TEMPERATURE = 10°C

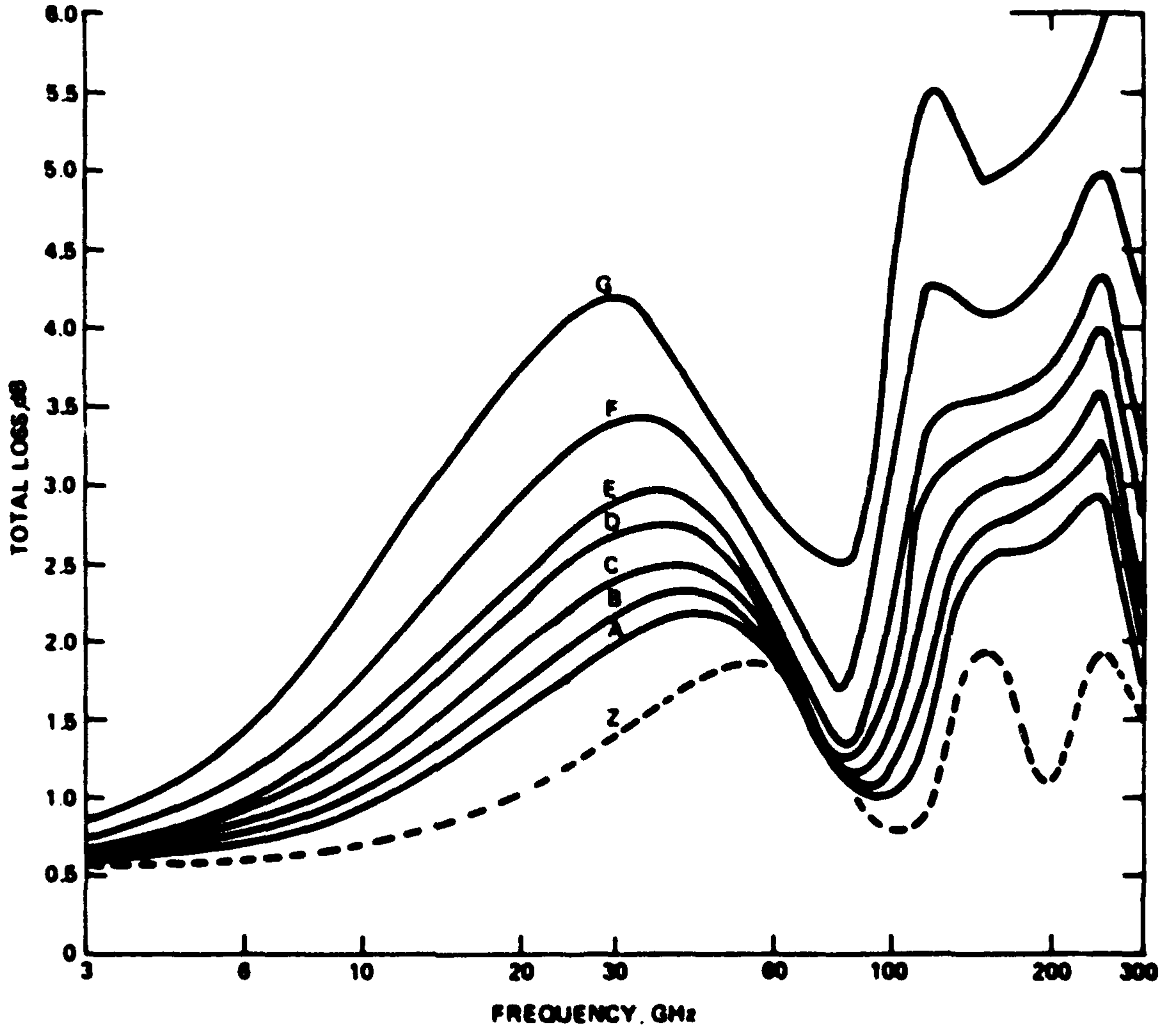


Figure 6-15. Attenuation Factor

6.3.3.4 (Continued)

The clear air attenuation, τ_{AIR}, is very small up to 60 GHz as can be seen from Figure 6-16. Therefore, it will be ignored.

The noise density, N_o, in equation (6-58) is given by:

$$N_o = \left[(k\ T_{SUN})^2+(k\ T_{EARTH})^2+(k\ T_{RECEIVER})^2+(k\ T_{RAIN})^2+\left(\frac{J}{W}\right)^2\right]^{1/2} \qquad (6\text{-}64)$$

T_{SUN} and T_{EARTH} are the noise temperatures for sun and earth when they fill the view of the receiving antenna. $T_{RECEIVER}$ and T_{RAIN} are the receiver noise temperature and the noise temperature due to heavy rain near the receiving antenna. k is Boltzman's constant. T_{EARTH} is zero for the backlink and T_{RAIN} is zero for both uplink and crosslink. A typical value for $T_{RECEIVER}$ is 1000^oK for today's satellite technology, T_{EARTH} is 254^oK, and T_{SUN} is between 10^4 and $10^{7o}K$ depending on the RF frequency and the sun's activity level. The noise caused by rain is shown in Figure 6-17, where it is evident that $10^{4o}K$ is a very liberal estimate for the noise temperature. Obviously if the sun fills the field-of-view of the antenna, it dominates the natural noise sources.

The last term, $\frac{J}{W}$, in equation (6-64) is caused by a broadband noise generating jammer which is assumed to exist at a distance R_{GJ} from the ground station, for the uplink/backlink case, or at latitude α_J and longitude β_J for the crosslink case.

The jammer noise power is spread evenly over the apparent bandwith, W, of the signal. J is the noise power at the receiver due to the jammer, and is determined by an equation similar to signal equation (6-59).

$$J = P_J G_J G_R(\phi_J)\left(\frac{\lambda_{RF}}{4\pi R_J}\right)^2 \qquad (6\text{-}65)$$

where P_J is the jammer transmitter power,

G_J is the jammer antenna boresight gain,

$G_R(\phi_J)$ is the satellite antenna gain in the direction of the jammer,

and R_J is the distance from the jammer, to the receiving antenna.

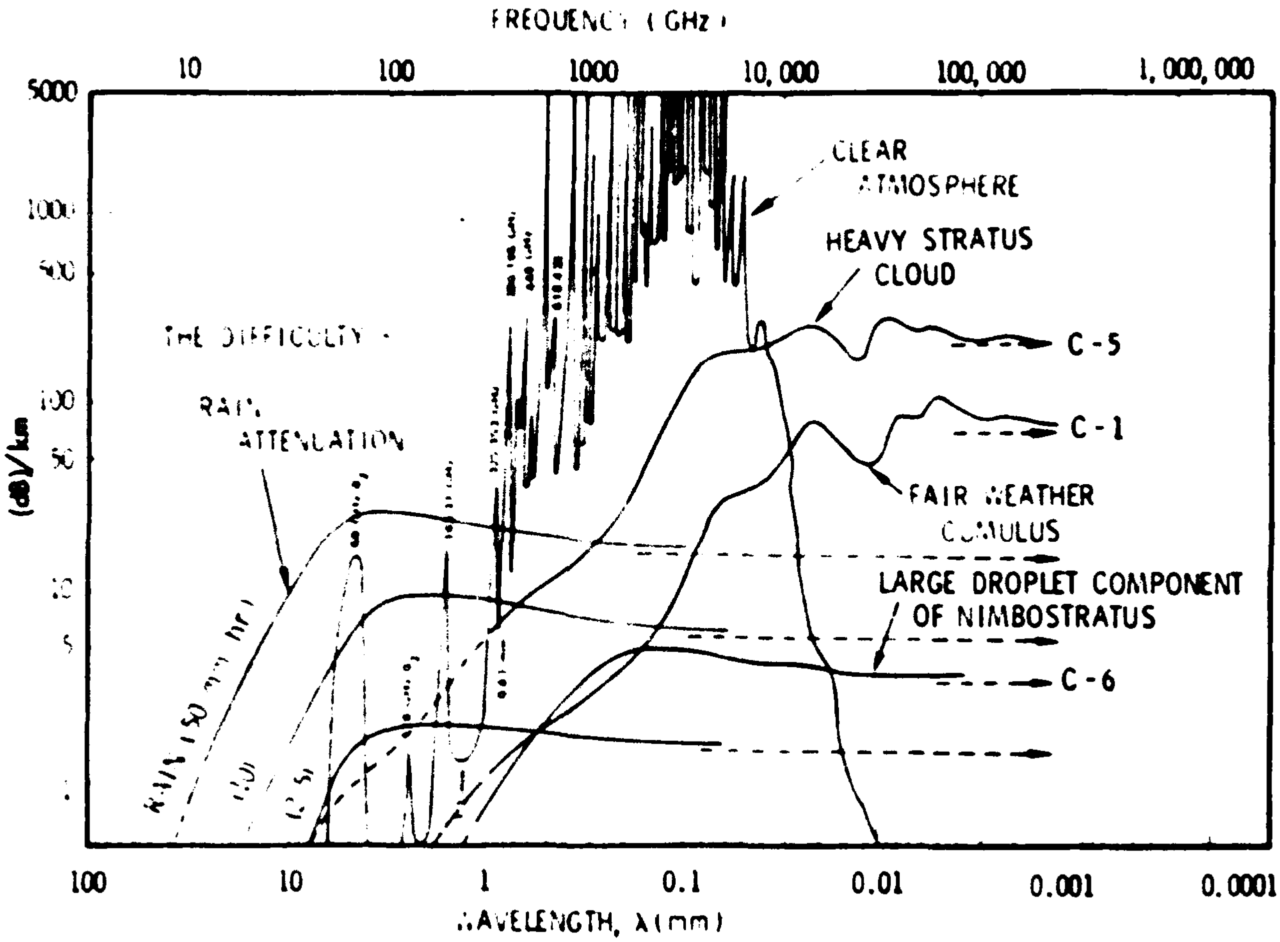


Figure 6-16. Summary of sea-level atmospheric attenuation

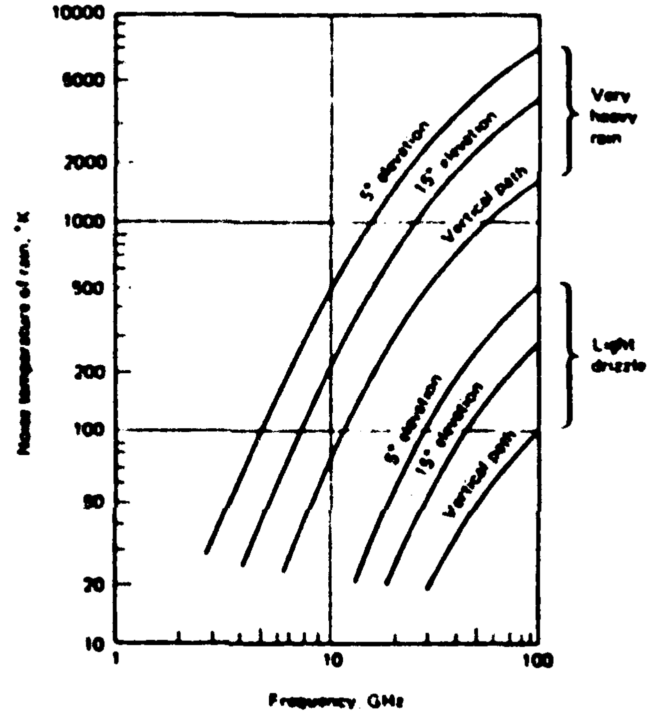


Figure 6-17. Noise caused by heavy cloud, fog, and rain

6.3.3.4 (Continued)

The rain related attenuation factors have not been included because the jammer's heavy rain statistics are assumed not to be well correlated with those of the ground site.

The gain profiles for both the ground station antenna and the satellite antenna are assumed to be that of a parabolic reflector, with tapering to lower the sidelobes to 25 dB below the main beam:

$$G_R(\phi_J) = \left(\frac{\pi D_{RF}}{\lambda_{RF}}\right) \eta_{RF} \left[\frac{2\, J_1(\chi)}{\chi}\right]^2 \quad \text{if } \chi < 3.6 \tag{6-66}$$

$$= \left(\frac{\pi D_{RF}}{\lambda_{RF}}\right)^2 \eta_{R} - 25\text{ dB} = \left(\frac{\pi D_{RF}}{\lambda_{RF}}\right) \eta_{RF} \left(\frac{1}{316}\right) \quad \text{if } \chi > 3.6$$

where $\chi = \dfrac{\pi D_{RF} \sin \phi_J}{\lambda_{RF}}$

D_{RF} is the receiving antenna diameter,

η_{RF} is the receiving antenna efficiency,

ϕ_J is the angle between the jammer and the antenna's boresight

and J_1 is the first order Bessel function of the first kind. The gain is maintained at $G_R(o)$-25 dB beyond the main lobe because it is assumed that jammer will be moved off the satellite antenna profile's nulls.

For the uplink:

$$\phi_J = \sin^{-1}\left(\frac{R_{GJ} \cos \phi_S^{RF}}{R_{GS} - R_{GJ} \sin \phi_S^{RF}}\right) \tag{6-67}$$

For the backlink:

$$\phi_J = \pi/2 - \phi_S^{RF} \tag{6-68}$$

6.3.3.4 (Continued)

For the crosslink:

$$\phi_J = \psi_{SLEW} \quad .$$

Inserting the terms into equation (6-58), the margins become:

$$M_u = \left[\frac{t_u}{B_u\left(E_{RF}/N_o\right)_c}\right] \frac{P_G\left(\frac{\pi^2 D_G^2}{\lambda^2}\ \eta_G\right)\left(\frac{\pi^2 D_S^2}{\lambda^2}\right)\eta_S\left(\frac{\lambda_{RF}}{4\pi\ R_{GS}}\right)^2 \quad \tau_{RAIN}\ \ \tau_{RADOME}}{\left[k^2\left(T_{SUN}^2 + T_{EARTH}^2 + T_{RECEIVER}^2\right) + \left(\frac{P_J G_J}{W}\ \ G_S(\phi)\left(\frac{\lambda_{RF}}{4\pi R_{JS}}\right)^2\right)^2\right]^{1/2}}$$

where
$$G_S(\phi) = \left(\frac{\pi D_S}{\lambda_{RF}}\right)^2 \eta_S \left[\frac{2\ J_1(\chi)}{\chi}\right]^2 \quad \text{if } \chi < 3.6$$

$$\left(\frac{\pi D_S}{\lambda_{RF}}\right)^2 \eta_S \left(\frac{1}{316}\right) \quad \text{if } \chi > 3.6$$

and
$$\chi = \frac{\pi D_S}{\lambda_{RF}} \quad \frac{R_{GJ}\cos\phi_S^{RF}}{R_{GS} - R_{GJ}\sin\phi_S^{RF}} \qquad (6\text{-}69)$$

6.3.3.4 (Continued)

$$M_B = \left[\frac{t_B}{B_B(E_{RF}/N_o)_c}\right] \left[\frac{P_S\left(\frac{\pi D_S}{\lambda_{RF}}\right)^2 \eta_S \left(\frac{\pi D_G}{\lambda_{RF}}\right)^2 \left(\frac{\lambda_{RF}}{4\pi R_{GS}}\right) \tau_{RAIN} \quad \tau_{RADOME}}{k^2\left(T^2_{SUN} + T^2_{RECEIVER} + T^2_{RAIN}\right) + \left(\frac{P_J G_J}{W} \quad G_G(\phi)\left(\frac{\lambda_{RF}}{4\pi R_{GJ}}\right)^2\right)^2}\right]^{1/2}$$

$$\text{where } G_G(\phi) = \left(\frac{\pi D_G}{\lambda_{RF}}\right)^2 \eta_G \left[\frac{2 J_1(\chi)}{\chi}\right]^2 \quad \text{if } \chi < 3.6$$

$$\left(\frac{\pi D_G}{\lambda_{RF}}\right)^2 \eta_G \left(\frac{1}{316}\right) \quad \text{if } \chi > 3.6$$

$$\chi = \frac{\pi D_G \cos \phi_S^{RF}}{\lambda_{RF}} \tag{6-70}$$

and τ_{RAIN} is a function of A_{UL}.

6.3.3.4 (Continued)

$$M_C = \left[\frac{t_c}{B_C\left(E_{RF}/N_o\right)_c}\right] \frac{P_S\left(\frac{\pi D_S}{\lambda_{RF}}\right)^4 \eta_S^2 \left(\frac{\lambda_{RF}}{4\pi R_{SS}}\right)^2}{\left[k^2\left(T_{SUN}^2 + T_{EARTH}^2 + T_{RECEIVER}^2\right) + \left(\frac{P_J G_J}{W} \; G_S(\Psi)\left(\frac{\lambda_{RF}}{4\pi R_{JS}}\right)^2\right)^2\right]^{1/2}}$$

$$\text{where } G_S(\Psi) = \left(\frac{\pi D_S}{\lambda_{RF}}\right)^2 \eta_S \left[\frac{2\, J_1(\chi)}{\chi}\right]^2 \quad \text{if } \chi < 3.6$$

$$\left(\frac{\pi D_S}{\lambda_{RF}}\right)^2 \eta_S \left(\frac{1}{316}\right) \quad \text{if } \chi > 3.6$$

$$\text{and } \chi = \frac{\pi D_S}{\lambda_{RF}} \sin \Psi_{SLEW} \tag{6-71}$$

Successful communication implies that these margins exceed unity and the line of sight conditions are met for crosslinks.

6.3.3.5 Area Allocation

Environmental resolution elements should be allocated to the satellites in such a manner as to minimize the time required to scan the coverage area. The Full OSCAR System Model calculates the figure of merit (FOM_{ij}) to every environmental resolution element for each satellite in the constellation. Because the time required to cover a resolution element is inversely proportional to the figure of merit, a more appropriate number to use in allocation considerations is the reciprocal of the figure of merit, called the G figure.

The initial allocation is accomplished by giving responsibility for each environmental resolution element to the satellite which can cover it using the lowest G figure. For each satellite, a summation of the G figures for those resolution elements for which it is responsible is calculated. To meet the time requirement, the sum for each satellite must be less than S_T, where

6.3.3.5 (Continued)

$$\boxed{S_T = \frac{(T_A)(A_{SQ})}{(A_{RE})(M_D)}} . \qquad (6-72)$$

If this condition is met, the allocation procedure is terminated and this initial satellite allocation is used.

When the time requirement is not satisfied, re-allocation is performed. For the satellite with the largest summation of G figures, the responsibility for one or more environmental resolution elements must be transferred until that satellite meets the temporal requirement. These environmental resolution elements must also be reassigned in such a manner as to provide a minimum amount of loading on the other satellites. To accomplish this, for each resolution element assigned to this satellite, the difference between G values for this satellite and the satellite with the next smallest G value is calculated and stored in a table named delta. The delta table is next sorted in increasing order while keeping careful account of the environmental resolution elements associated with each value in the delta table. In this manner, a sorted environmental resolution element table is created. Since the smaller the value in the delta table, the less the impact of area reassignment is upon the other satellites, resolution elements are reassigned to the satellites with the next lowest G figures, in the order that they appear in the sorted table. Elements are reallocated until the G figure summation becomes less than S_T. The remaining environmental resolution elements will comprise the final area allocation to this satellite.

A summation of the G figures for the remaining satellites must now be computed. The summations are again checked to see whether or not they meet the temporal requirement. If the requirement is satisfied for all the satellites, the allocations are completed. Should the requirement not be met, the procedure of forming the delta table and performing enviromental resolution element reassignments for that satellite with the largest G figure summation must be repeated. This procedure continues until all satellites satisfy the time requirement, or until all satellites have received their final allocations via the process described above.

6.3.3.6 Remote Sensor Performance

Information derived from a "remote sensor" is desirable at both the submarine terminal and the satellite. This section discusses the information desired and the method(s) of obtaining it.

6.3.3.6.1 Submarine Remote Sensor

In order to optimize the performance of the Submarine Terminal, we can vary:

1. Receiver Field-of-View;
2. Receiver pointing angle relative to zenith and local longitude;
3. Detection Bandwidth;
4. Post Detection Filtering;
5. Post Detection Processing;

and, depending on the optical filter type,

6. Filter center wavelength (λ) and the bandpass ($\Delta\lambda$).

In our previous development of the SPDPM, we have assumed that:

a. The receiver field-of-view is fixed;

b. It is optimum to point the receiver at the signal ($\xi = 0$);

c. The received pulse shape is known, and that using

$$B = \frac{0.4}{\Delta t_{1/2}}$$

results in optimum and lossless detection, filtering and processing.

If we further assume that there is a "set" aboard the submarine whose purpose it is to derive enough information so that those six parameters will be optimally selected, we note that in operation the information available to this remote sensor set will include:

1. Satellite locations;
2. Sun/Moon location;
3. Receiver location and depth;

6.3.3.6.1 (Continued)

4. Submarine Speed;
5. Time-of-Day;
6. Time-of-Year;
7. Average Water Data Base there and then;
8. Average Cloud Data Base there and then;
9. Average background level in the operating passband;
10. Verified Propagation Path Models.

The key inputs are the last two, since one may be able to derive the characteristics of the propagation path from passive measurements of the existing background. However, the following information could also be made available:

11. Long range cloud forecasts;
12. Thermocline locations and strength;
13. Relative spectral strength of background;
14. Previous pulse characteristics;
15. Background short term fluctuation properties;
16. Background long term time dependence;
17. Short term weather pattern update (night before).

On another contract we are developing techniques for using all or part of these 17 data inputs to provide the required information on the submarine, and are proposing that experimental verification of these techniques be performed under the development tests defined in Section 9, Volume 4 of the final report.

In the meantime, we take as a submarine remote sensor model:

a. The receiver field-of-view is fixed at a single value, independent of the propagation path;

b. The receiver optical axis is pointed exactly back at the axis of the incoming signal;

c. The received pulse shape and width is exactly known, and lossless detection electrical filtering and processing occurs for the detection bandwidth, B, equal to 40% of the reciprocal of the half power pulse width, $\Delta t_{1/2}$.

6.3.3.6.1 (Continued)

Further analytic and experimental work will certainly modify one, or all three, portion(s) of this model.

6.3.3.6.2 Satellite Remote Sensor

The remote sensing "set" of the satellite terminal could provide information to optimize the following satellite transmitter characteristics (assuming a single "black box" laser operating at a single value of E_p and PRF is available):

1. Transmitter beamwidth;
2. Number of revisits to a given location;
3. Message type (Selective call vis-a-vis General Broadcast, for example);

and if a tunable laser and filter are available:

4. Wavelength (λ).

In our present development of the SPDPM and DCM, we have assumed that:

a. The satellite transmitter beamwidth is perfectly matched (for the fully adaptive scan) to the propagation path losses in a given environmental resolution element (ERE), so that the required signal-to-noise ratio is exactly matched with the actual signal-to-noise ratio;

b. No revisits to a given location occur;

c. The message type is pre-selected before a DCM run, and is not of prime importance since the system is designed to meet the EAM requirements.

The "set" responsible for determing the scan pattern, revisits, and message type will have the following available information:

1. Outputs from all available remote sensors on other satellites;
2. Real Time weather updates from the ground/ships ("ground truth");
3. Coverage Area Location;
4. Data from the previous time interval;

6.3.3.6.2 (Continued)

5. Average Cloud Data Base for that time and place;
6. Average Water Data Base for that time and place;
7. Time of Day;
8. Time of Year;
9. Verified Propagation Path Models.

On another contract we are developing techniques for using all or part of these nine data inputs to provide the information required by the satellite remote sensor set. A significant portion of the other program is devoted to determining the state-of-the art of available and planned remote sensors, and in determining their accuracy in estimating the key cloud, air-water interface, and water properties.

We are proposing that experimental verification of the resulting techniques be performed under the Development Tests, defined in Section 9, Volume 4 of the final report.

In the meantime, we take as a satellite remote sensor model:

A. A perfectly adaptive scan controls the satellite transmitter beamwidth;

B. No revisits to a given location occur; if the FOM_{ij} <1, then the ij'th ERE is not illuminated at all;

C. The system is designed to deliver an EAM; the system knows enough to send a Selective Call message (to maintain connectivity) where a General Broadcast message would require too much time, and so lower the system effectiveness.

6.4 MODEL IMPLEMENTATION

The architecture for the Full OSCAR System Model has been developed in the previous sections. It is not within the scope of this contract to implement a computer program for this FOSM, but it is part of this contract to perform sample calculations using all elements of the FOSM to show example results.

These sample calculations are performed in Section 3 of Volume 4 of this final report. They occur after:

1. A configuration trade-off has been performed in Section 2 of Volume 4. This trade-off results in optimum satellite configurations (orbits and number of satellites) for three types of orbits: geostationary, 12-hour period highly elliptical, and 24-hour period highly elliptical;
2. The SPDPM is evaluated for a range of signal, sun, and moon zenith angles, and cloud and water types;
3. The DCM is evaluated in Section 3.4 of Volume 4 for satellites in the best configurations, fully adaptive scan, time of peak demodulation, data bases for clouds and water provided by NOSC, a single time interval during which the sun is at $+ 23.5^\circ$ latitude over the center of the satellite's area coverage responsibility, for the EAM, and typical system design parameters. The downlink availability is scaled to meet the minimum system requirement by deriving a required technology figure of merit:

$$\boxed{TECH_{FOM} \quad F_L P'_L \left(\frac{\gamma_R}{B_{OPT}}\right)^{1/2}} \quad , \qquad (6\text{-}73)$$

for F_L = wall plug laser efficiency;

P'_L = prime power available on the satellite to pump the laster;

γ_R = receiver (primarily optical filter) transmission;

B_{OPT} = optical filter bandpass.

6.4 (Continued)

Then the best of the satellite configurations is chosen as that one requiring the fewest satellites and the smallest value of $TECH_{FOM}$.

Based on these results, we perform the following sample calculations in Volume 4 for the FOSM:

Environmental Inputs:	Half the runs with Worst Case NOSC models for clouds and water, Half with the Best Case;
	No ice blockage;
	Sun/moon location in Table 6-4
Requirement Inputs:	Full area coverage and full depth EAM
	Full System Effectiveness.
System Design Inputs:	$TECH_{FOM}$ and satellite network from DCM.
	Other system design inputs from DCM.
	No crosslink.
	Uplink assumed not to be a driver, but specified.
	No MTBF's or MTTR's for any portion of this link.
	For each of the 12 runs, place one satellite at apogee over an ocean, and allocate the other coverage as appropriate. Alternate the ocean over which the satellite is at apogee in every other run.

6.4 (Continued)

TABLE 6-4. SUN/MOON LOCATIONS FOR SAMPLE FOSM RUNS

SUN		MOON	
LONGITUDE	LATITUDE	LONGITUDE	LATITUDE
0	0	180°	+5.1°
0	+23.5°	180°	+28.6°
0	-23.5°	180°	-18.4°
90°	0	270°	+5.1°
90°	+23.5°	270°	+28.6°
90°	-23.5°	270°	-18.4°
180°	0	0	+5.1°
180°	+23.5°	0	+28.6°
180°	-23.5°	0	-18.4°
270°	0	90°	+5.1°
270°	+23.5	90°	+28.6°
270°	-23.5°	90°	-18.4°

For each of the 12 runs, we calculate a downlink availability. Then the average downlink over the year is taken as the average of these results (weighting the 0° solar latitude results twice).

Given this downlink availability, then, reasonable values will be assigned to the other four portions of the link to arrive at a system-effectiveness which meets the OSCAR requirement.

6.5 DISCUSSION OF ANALYSES

The analyses developed in Section 6.3 differ markedly in their status.

6.5.1 Environmental Models

The sub-models for the predictable data bases presented in Section 6.3.1.1 are not uncertain. Although they are only approximations, the results are adequate for predicting OSCAR performance.

6.6 "Parameter Value" Uncertainties

The parameter value uncertainties for the FOSM include those of the SPDPM and DCM, but also extend to others.

6.6.1 Environmental Parameters

The parameter values for the fixed data bases are well known, and the only uncertainty in the predictable data bases is the exact values for IC_{ij}, fractional ice coverage, to use for a particular ij'th environmental resolution element during a particular month. This only affects a percent of the total coverage area, so the uncertainty is not of prime importance.

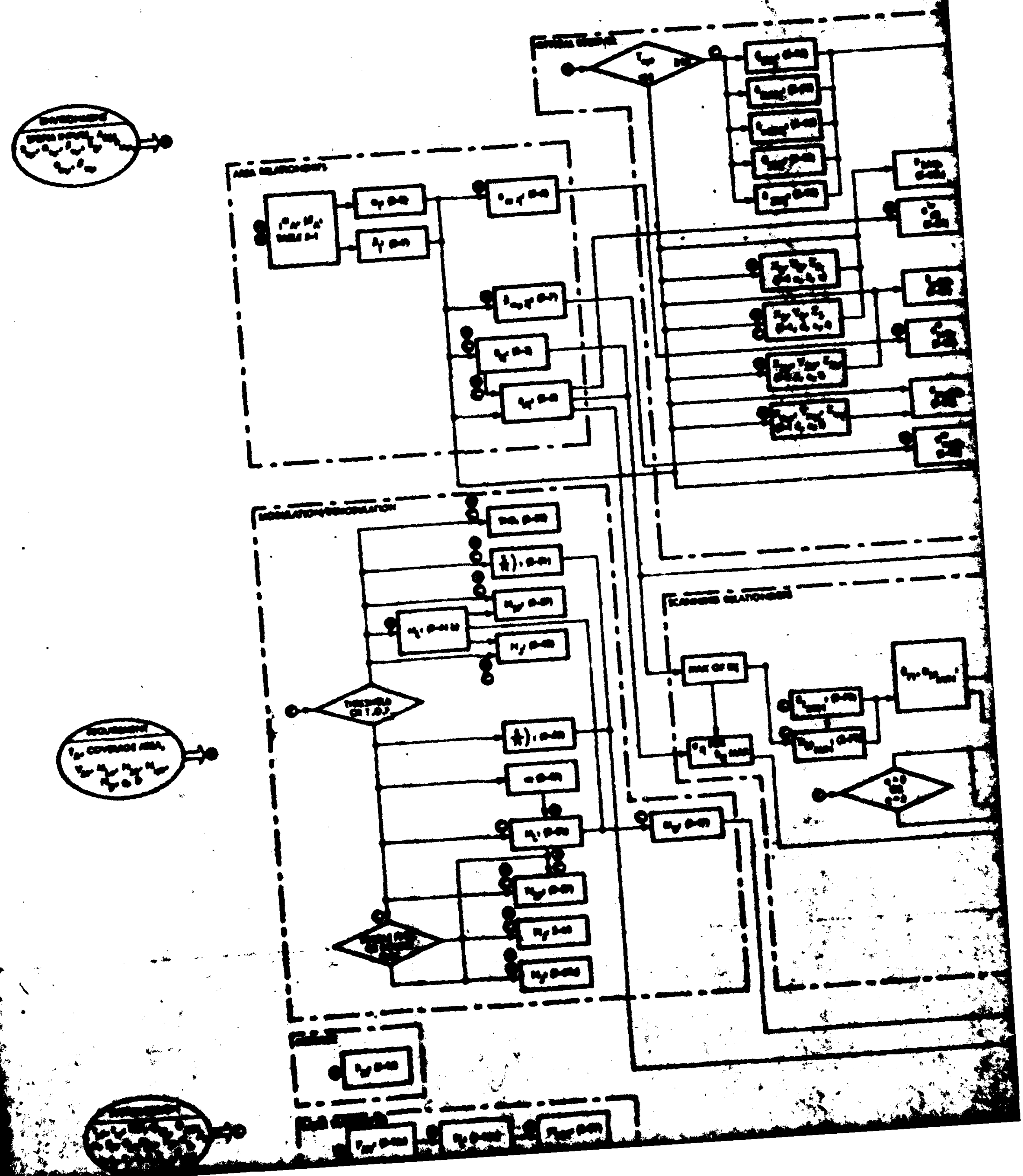
The unpredictable data bases of cloud properties, air-water interface properties and water properties are largely uncertain. In addition to those problems pointed out in the SPDPM and DCM sections; the global, seasonal and diurnal properties now become of importance. In particular, the mean time between outages and mean time to clear are not known at this time, along with real distributions and evolutions of cloud thickness and average extinction coefficient, depth of the thermocline and diffuse attenuation coefficient above and below this thermocline, and the strength and characteristics of bioluminescence.

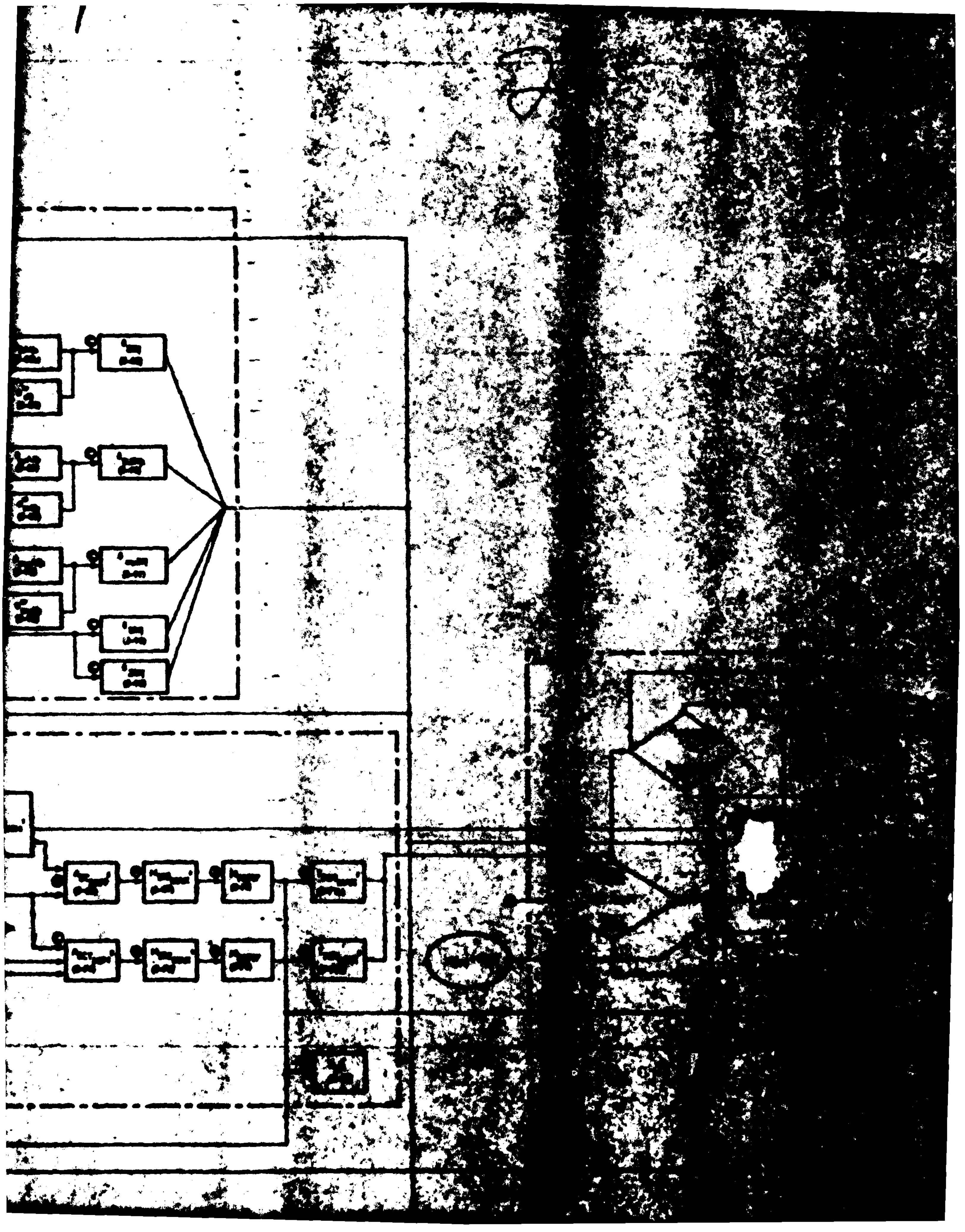
Table 6-5 summarizes only those FOSM input parameters which are uncertain.

Table 6-5. Uncertain Parameters for the FOSM

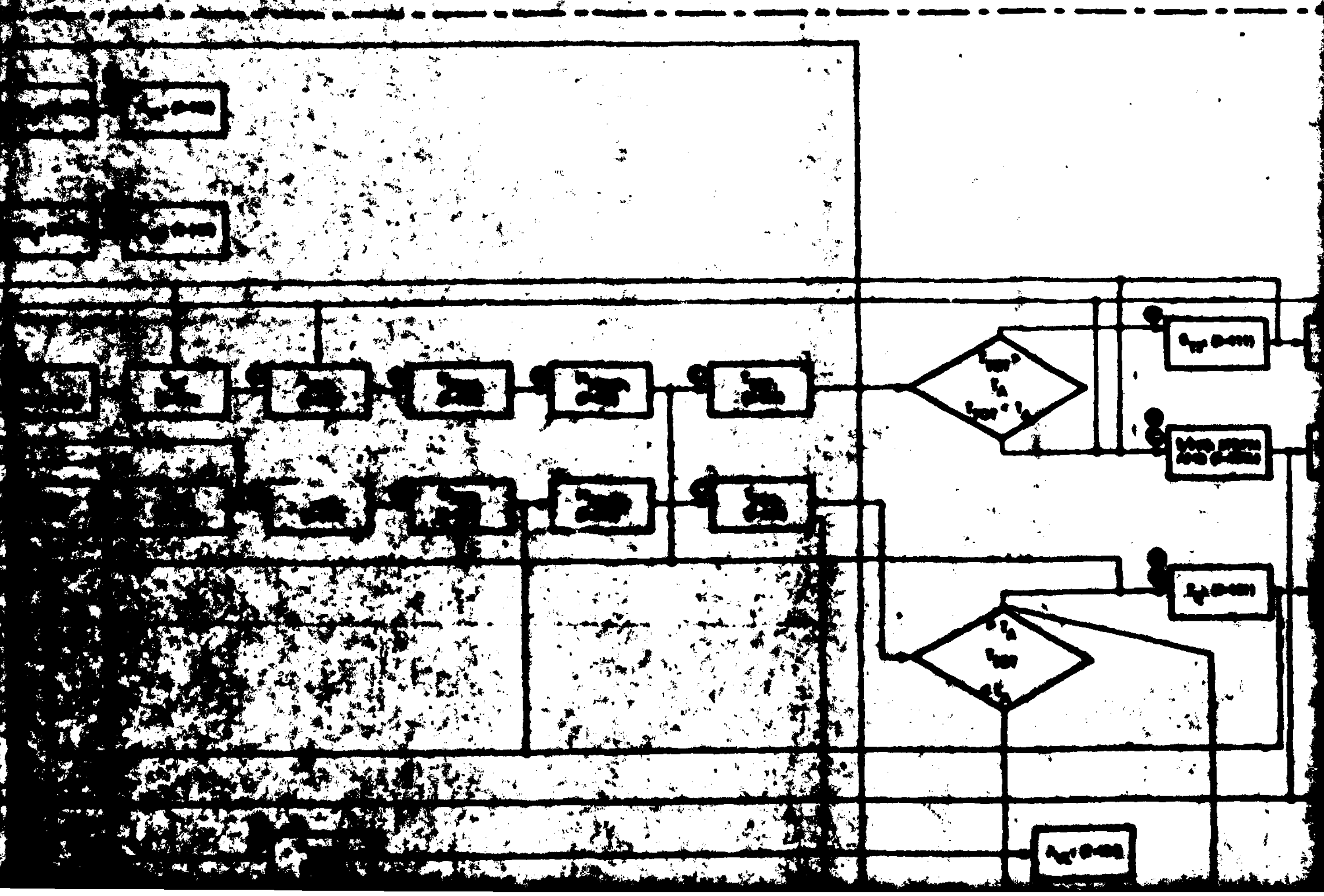
PARAMETER	COMMENTS
ENVIRONMENT	
ICE COVERAGE	A SMALL EFFECT
CLOUD DISTRIBUTION PARAMETERS	NEEDS TO BE RESOLVED
AIR-WATER INTERFACE PARAMETERS	A RELATIVELY SMALL EFFECT
WATER DISTRIBUTION PARAMETERS	NEEDS TO BE RESOLVED

1

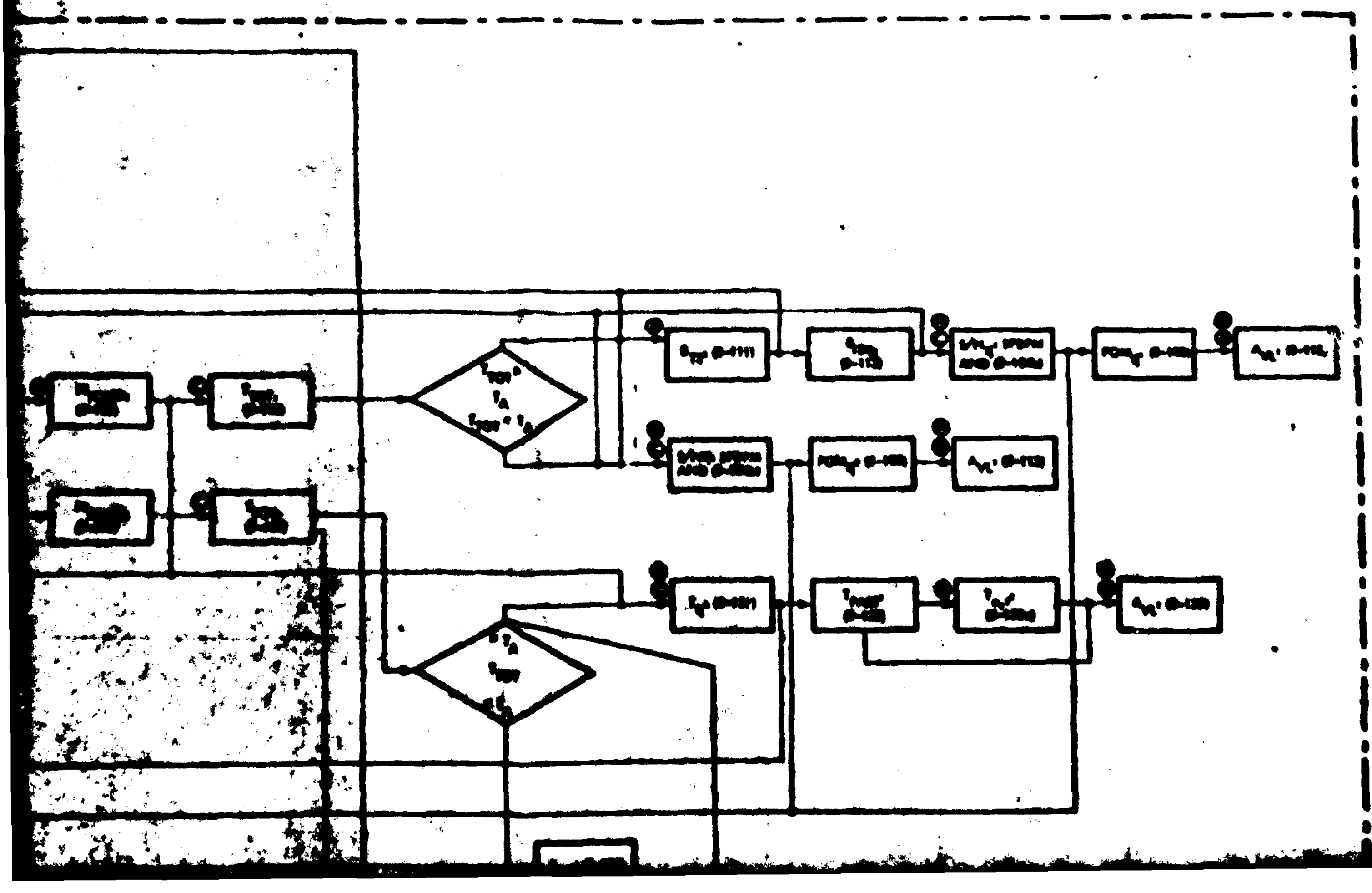


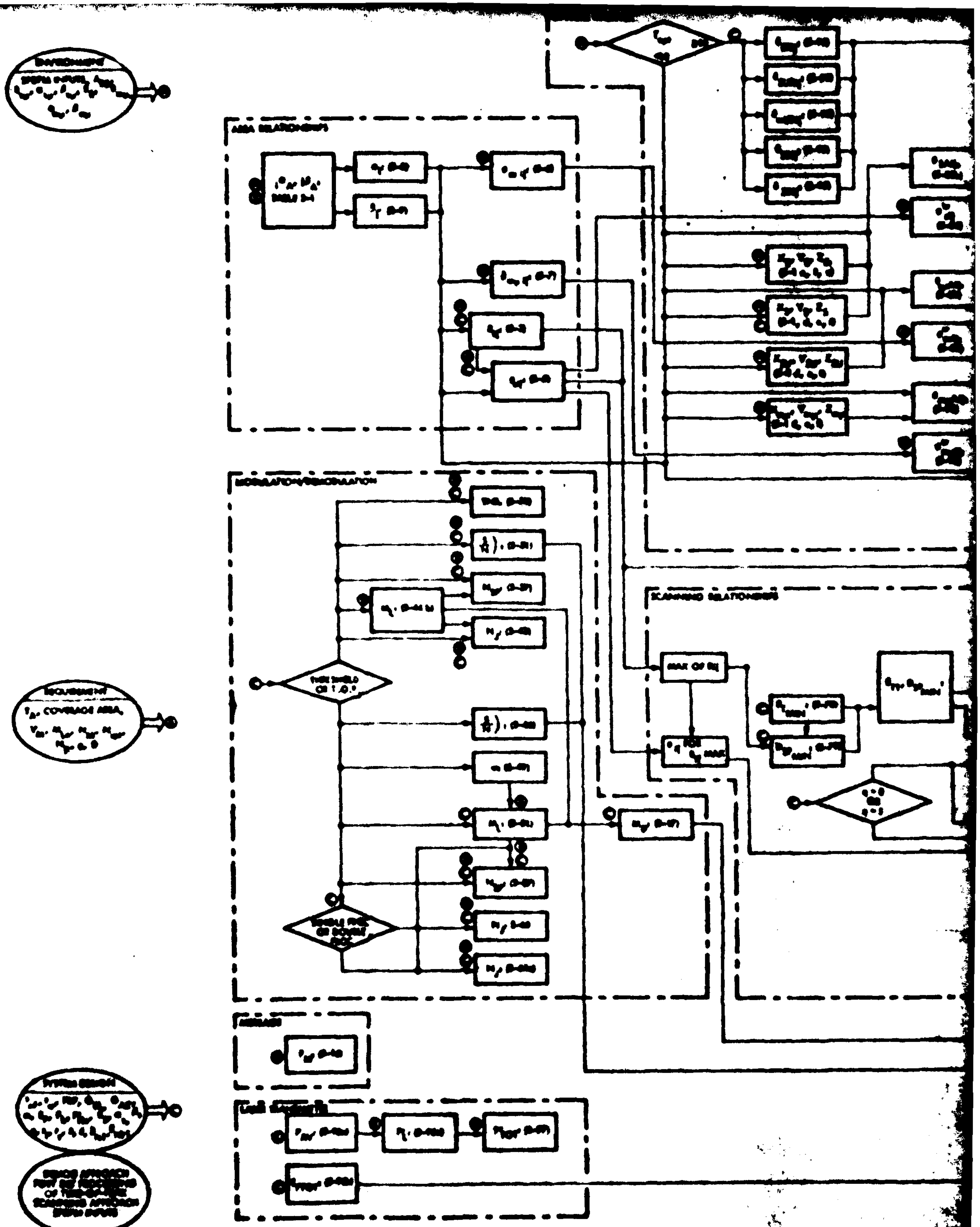


3



3 1 4




AREA RELATIONSHIPS
MODULATION/DEMODULATION
SCANNING RELATIONSHIPS
MAX OF R(i)
REQUIREMENT
COVERAGE AREA,

5

1